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Air Pollution Technology, Inc.

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June 1976

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16. ABSTRACT The report gives results of the computation of fine particle collection efficiency as a function of particle size, based on data from an Air Pollution Systems, Inc. (A. P. S.) electrostatic scrubber. The scrubber was operated at 21.0 and 22.7 actual cu m/min at 16C with a pressure drop of approximately 40 cm W. C. Titanium dioxide was generated as the test aerosol having an approximate mass mean diameter (aerodynamic) of 1.0 micrometer with a geometric standard of 2.2. The scrubber was tested with the particle ionizer on and off: collection efficiency generally improved with the ionizer on. Additional testing was performed to determine if static charges were affecting the sampling measurements. Particle size and collection efficiency changed when charge neutralizing devices were used. The inlet test aerosol charge apparently affects the measured penetration.

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Electrostatics	Electrostatic Scrubbers	20C
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A. P. S.
ELECTROSTATIC SCRUBBER
EVALUATION

by

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ABSTRACT

Fine particle collection efficiency as a function of particle size has been computed from data taken on an Air Pollution Systems, Inc. Electrostatic Scrubber.

The scrubber was operated at 21.0 and 22.7 Am^3/min at 16°C with a pressure drop of approximately 40 cm W.C. Titanium dioxide was generated as the test aerosol having an approximate mass mean diameter of 1.0 μmA with a geometric standard of 2.2.

The electrostatic scrubber was tested with the particle ionizer on and off. Test results showed a general improvement in collection efficiency when the ionizer was turned on.

Additional testing was performed to determine whether static charges were affecting the sampling measurements. Changes in particle size and collection efficiency measurements occurred when charge neutralizing devices were used. There is apparently an effect of inlet test aerosol charge on the measured penetration.

CONCLUSIONS

This evaluation was one of a series of such evaluations being conducted by the Industrial Environmental Research Laboratory of the Environmental Protection Agency to identify and test novel devices which are capable of high efficiency collection of fine particulates. The test methods used were not the usual compliance-type methods but were, rather, state-of-the-art techniques for measuring efficiency as a function of particle size using a cascade impactor and diffusion battery upstream and downstream from the A.P.S. Electrostatic Scrubber.

Experimental rest results for a TiO_2 test aerosol, which has a mass mean diameter as dispersed of approximately 1.0 μmA and a standard deviation of 2.2, on the Air Pollution Systems electrostatic scrubber show overall penetration ranging from 0.03 to 0.17 with the ionizer on for a pressure drop across the system of 43 cm W.C. With the ionizer off, the electrostatic scrubber becomes a standard venturi with penetration ranging from 0.1 to 0.34 at 43 cm W.C.

Using the experimental data and the average overall penetrations, effective cut diameters (i.e. the cut diameter for a conventional high energy scrubber with the same overall penetration) for the scrubber with the ionizer on and off were determined. The effective cut diameter computed for the ionizer on ranged from 0.23 to 0.54 μmA and from 0.42 to 0.66 μmA for the ionizer off.

Static charges induced by the dust feeder had a significant effect on the sampling measurements. Additional charge neutralizers placed prior to the impactors eliminated static charges in the impactors. It is possible that electrostatic

forces caused by the static charges biased the inertial impaction collection mechanism in the cascade impactors. Cut diameters were higher for both ionizer on and off operation when the charge neutralizers were used on the dust feeder.

The correlation of cut diameter with pressure drop for venturi scrubbers corresponds closely with the experimental data found for the scrubber with the ionizer off during these tests. This gives evidence that the results obtained without charge neutralizers prior to the impactors were influenced by charged dust particles. Additional tests of this scrubber on aerosols which are either known to be electrically neutral or are actual emissions should be made before a conclusive definition of its merits can be given.

Addition of the ionizer section prior to the venturi increases the efficiency of the system with no appreciable additional power requirement. The A.P.S. system may be an economic improvement on conventional scrubber systems, depending on the cost for modification of the present system being used. The operating cost advantage in using the ionizer is estimated in this report. However, no determination can be made at this time to warrant use of the A.P.S. system without real cost figures of an actual installation.

INTRODUCTION

Air Pollution Technology, Inc. (A.P.T.) conducted a performance evaluation of the Air Pollution Systems, Inc. (A.P.S.) Electrostatic Scrubber, in accordance with E.P.A. Contract No. 68-02-1496, "Experimental Tests of Novel Fine Particulate Collection Devices".

The objective of the performance test was to determine fine particle penetration as a function of particle size and scrubber parameters.

Simultaneous inlet and outlet particle sampling measurements were taken on the scrubber during a test period from June 16 through June 27, 1975. Additional testing was performed on July 17 and 18, 1975 to determine whether static charges were affecting the sampling measurements.

In-stack cascade impactors, total filters, condensation nuclei counters and a portable diffusion battery were used to obtain mass loadings and size distribution data. The results of these series of tests on Air Pollution Systems's Electrostatic Scrubber are presented in the text.

SOURCE AND CONTROL SYSTEM

The pilot scale "Electrostatic Scrubber" of Air Pollution Systems is basically an electrostatic charger (or ionizer) followed by a venturi scrubber. Figure 1 is a schematic diagram of the pilot system. An electrode is placed upstream of the venturi to charge the inlet particles, which then enter the venturi throat. The gas stream atomizes the central water spray in the venturi throat and the charged particles, according to A.P.S., are then attracted and collected by the highly polarized water molecules. The charged particles are also collected on the walls of the ionizer section prior to the throat of the venturi. A thin film of water is run down the inclined surfaces to keep the walls clear and prevent high voltage arcing. The particle laden water droplets are then collected by a cyclonic separator and sent into a settling tank (clarifier). The water can then be recycled back into the scrubber system. However, during the test program, fresh water was used.

The ionizer consists of an electrode supported in the inlet of the venturi section. According to Air Pollution Systems, a stable electrical discharge of high intensity is maintained across the venturi throat between the center electrode and the wall. A.P.S. claims that the average field that can be maintained across the electrode gap (space between the electrode probe and the wall) is substantially higher, 11-16 kV/cm, than that of a standard electrostatic precipitator, 4 kV/cm.

The pilot scrubber has a maximum capacity of 28 Am^3/min (1,000 ACFM) at 16°C. Under testing conditions the scrubber was operated at 21.0 Am^3/min (740 ACFM) @16°C and at 22.7 Am^3/min (800 ACFM) @16°C. Liquid flow rates (total) were set at 30.3 ℓ/min and 41.7 ℓ/min during the test program. L/G ratios were 1.4 ℓ/m^3 and 1.8 ℓ/m^3 respectively

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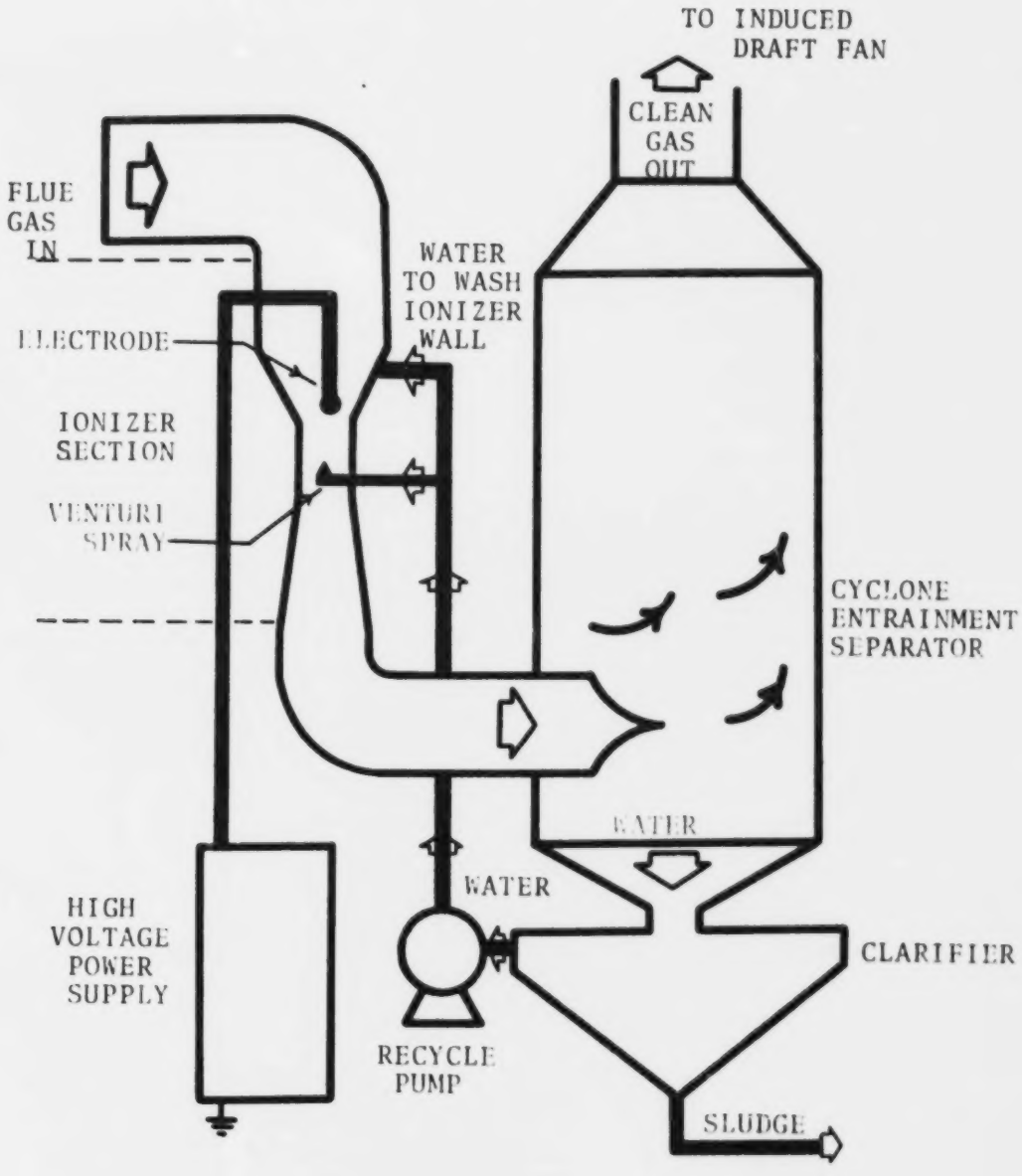

Figure 1. APS Electrostatic Scrubber

for the above flow rates. Electrode probe cooling air was introduced at a rate of 1.1 m^3/min (40 CFM). The addition of the cooling air was accounted for as dilution air in the outlet sample calculations.

A 3 horsepower induced draft fan with a capacity of 28 Am^3/min at a pressure of 45 cm W.C. was located downstream of the outlet sample ports. Gas flow rates were adjusted through a damper upstream of the fan.

The test aerosol used during this study was titanium dioxide, TiO_2, which has a density of 3.0 g/cm^3. The mass median diameter of TiO_2 aerosol was approximately 1.0 microns aerodynamic, μmA, as dispersed, with a standard deviation of 2.2.

A schematic diagram of the particle generator used during the test program is given in Figure 2. An auger feeds the aerosol to an intermediate blower, which in turn forces the dust into a deglomerating chamber. The chamber contains a series of orifices which tend to break up the large particles. The aerosol is then injected into the sample duct by the main blower.

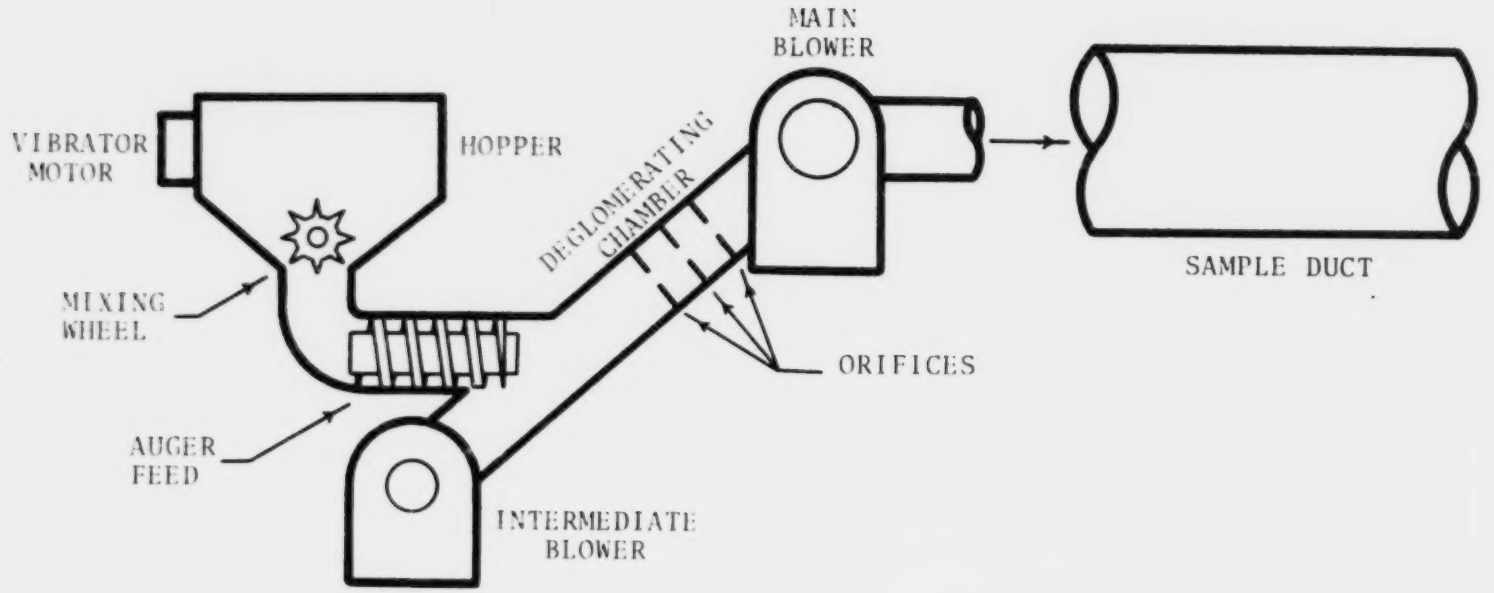

Figure 2 - Schematic Diagram of Particle Generator

TEST METHOD

The performance characteristic of the electrostatic scrubber was determined by measuring the particle size distribution and mass loading of the inlet and outlet gas sample simultaneously.

For the first tests performed in June 1975, modified E.P.A. type sampling trains with in-stack University of Washington Mark III (U.W.) cascade impactors were used for particle measurements above 0.3 μmA. Figure 3 shows a schematic diagram of the modified sample train. Greased aluminum substrates were used in the impactors to prevent particle bounce and minimize wall losses.

The Air Pollution Technology portable screen diffusion battery (A.P.T. - S.D.B.) was used for particle measurements from 0.1 μm to 0.01 μm (actual).

The A.P.T. - S.D.B. uses Brownian diffusion to accomplish the size fractionation of particles smaller than ~0.1 μm. Because smaller particles diffuse more readily than larger ones, successively larger particles are captured as they proceed through the battery.

Using a condensation nuclei counter (CNC) to determine the total number of particles at various points in the battery, one can obtain data which will correspond to a unique size distribution. The size distribution computation is based on calibration of the S.D.B. in the A.P.T. laboratory.

Computation of size distributions from the data on penetration is accomplished through the use of measurements of density, pressure, temperature, flow rate, and moisture, in addition to the C.N.C. calibration factors.

During an impactor run, several inlet and outlet fine particle size measurements were taken alternately with

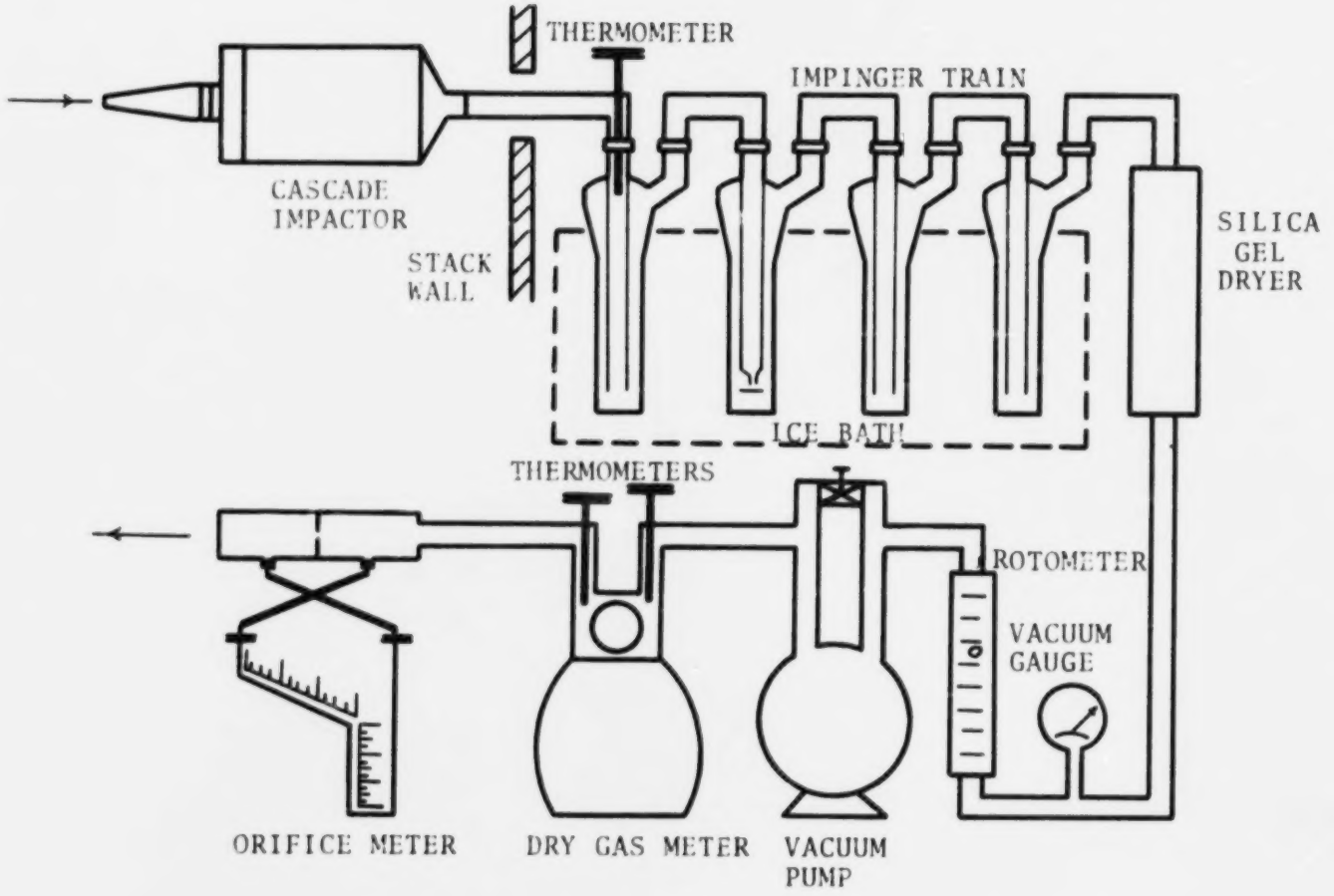

Figure 3 - Modified E.P.A. sampling train with in-stack cascade impactor.

the portable diffusion battery. Since the system remained fairly constant during each run, alternate inlet and outlet S.D.B. measurements were considered to approximate simultaneous sampling.

In-stack filter samples were also taken to obtain total particulate loadings and overall collection efficiencies of the system.

Impactor blank runs were performed periodically to assure that the greased aluminum substrates did not react with the stack gases. A blank impactor run consists of an impactor preceded by two glass fiber filters run at identical sample conditions as the actual sampling runs. Total filter loadings were also obtained during the blank impactor run to furnish simultaneously inlet and outlet mass concentration and overall collection efficiency data.

Additional tests were performed in July 1975 to determine whether static charge caused by the particle generator was affecting particle collection in the impactors. Polonium 210 charge neutralizers (Staticmaster, Ionizing unit-Model No. 2U500) were connected prior to the impactors on both the inlet and the outlet. Figure 4 is a schematic diagram of the sample systems used during this series of testing. In order to check the possibility that particle charge might affect scrubber performance when the ionizer is off, a charge neutralizer was added to the dust disperser. A two foot glass tube containing six Staticmasters was placed on the end of the particle generator.

Gas flow rates for all tests were determined by means of a calibrated standard-type pitot tube along with in-stack taps for continuous wet and dry bulb temperatures and velocity head measurements. Velocity traverses of the inlet and outlet were performed according to the E.P.A. standards and average velocity points selected for one point sampling. Sample flow rates were measured with the usual E.P.A. train instruments so as to obtain isokinetic sampling.

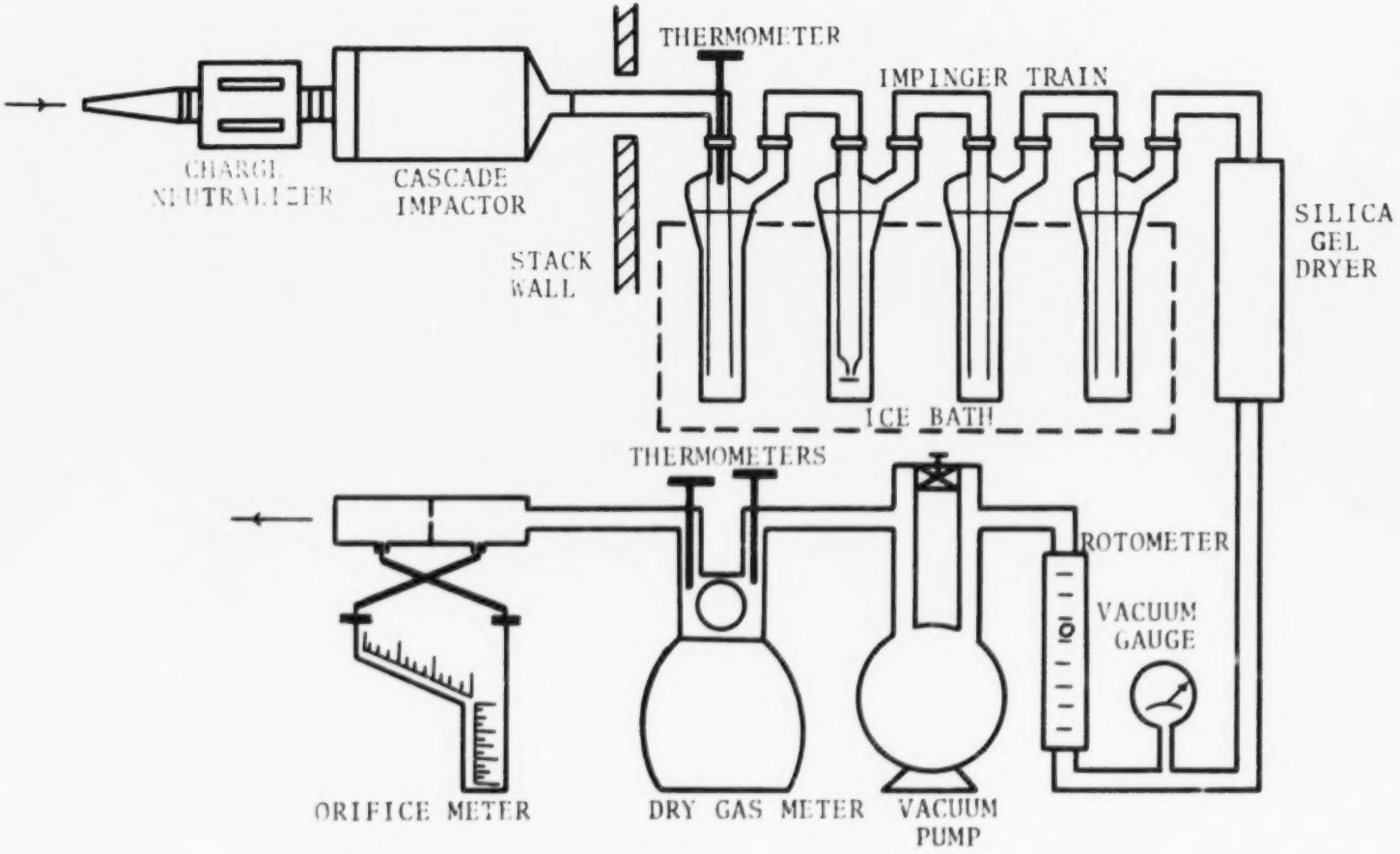

Figure 4 - Modified E.P.A. sampling train with in-stack cascade impactor and charge neutralizer.

The inlet sample port was located eleven duct diameters downstream from the dust feeder and fourteen diameters upstream of the nearest disturbance. The outlet port was located twelve duct diameters downstream of the nearest disturbance and eight duct diameters upstream of the induced draft blower. Velocity traverses of both the inlet and the outlet revealed fully developed flow profiles.

CONDITIONS FOR RUNS

A total of thirty-one simultaneous inlet and outlet sample runs were performed on the electrostatic scrubber. Four separate sets of sample data were obtained during the series of tests conducted on the pilot system.

During the first three series of tests (data sets A, B, and C) the scrubber was tested with the ionizer on and off and during the fourth series (data set D) with the ionizer on.

The scrubber was tested at 21 Am^3/min (740 ACFM) at 16°C for the first series of tests (runs 1-10, data set A). The pressure drop across the venturi was 40 cm W.C. with liquid flow rates to the ionizer wall wash and the venturi throat set at 7.6 ℓ/min and 22.7 ℓ/min respectively.

The second series of tests (runs 11-26, data set B) were run at 22.7 Am^3/min (800 ACFM) at 16°C with the same pressure drop across the venturi of 40 cm W.C. The liquid flow rate was increased to 34.1 ℓ/min at the venturi throat and the ionizer wall wash remained the same at 7.6 ℓ/min. An overhanging gasket and water feed tube were removed from the scrubber throat between sets A and B .

The third series of tests (runs 27-30, data set C) were run at identical operating conditions as the second series. These runs were taken to determine the effect of the static charge induced by the aerosol generator. A cross shaped baffle was introduced into the test aerosol mixing duct prior to set C , in order to cause better mixing of air and the aerosol stream from the dust blower.

Finally, the last series of runs attempted used alumina as a test aerosol instead of titanium dioxide. Due to particle generator plugging, run 31 (data set D) was the only test performed on this aerosol.

The inlet mass loading was also varied during the testing period. The scrubber was tested on various inlet loadings with the ionizer on and off. A summary of the characteristics of each test, such as run number, mass loading, flow rates, ionizer on or off, and the sample device used (impactor, filter, diffusion battery) are given in Table 1.

Table 1 . TEST RUN SUMMARY

DATE	RUN NO.	SAMPLE DEVICE(1)		IONIZER	MASS LOADING mg/DNm^3	
		Inlet	Outlet		Inlet	Outlet
6/17	1 (set A)	F(2)	B	ON	-----	1.0
6/18	2 "	I	I	ON	146.5	12.8
6/18	3 "	I	I	ON	156.1	12.0
6/18	4 "	I	I	ON	188.5	16.1
6/19	5 "	I	I	OFF	524.6	75.2
6/19	6 "	I	I	OFF	396.1	62.1
6/19	7 "	F	F	OFF	185.1	62.4
6/20	8 "	F	F	OFF	927.9	108.2
6/20	9 "	F	F	ON	1081.2	37.7
6/20	10 "	F	B	OFF	218.7	41.8
6/23	11 (set B)	I	I	ON	152.7	10.3
6/23	12 "	F	B	ON	132.0	13.8
6/23	13 "	I	I	ON	153.4	11.4
6/24	14 "	I	I	OFF	216.9	40.8
6/24	15 "	F	F	OFF	594.2	79.2
6/24	16 "	I	I	OFF	516.9	65.1
6/25	17 "	F	F	ON	472.4	24.2
6/25	18 "	I	I	ON	495.9	18.4
6/25	19 "	F,D	B	ON	69.4	8.4
6/25	20 "	I	I	ON	192.2	12.5
6/26	21 "	I,D	F	ON	48.1	8.1
6/26	22 "	I,D	F	ON	53.7	7.6
6/26	23 "	I,D	F	ON	100.1	10.3
6/27	24 "	I	I,D	ON	85.1	12.7
6/27	25 "	F	I,D	OFF	153.9	31.8
6/27	26 "	I,D	F	OFF	102.6	21.3
7/17	27 (set C)	I,D (3)	I,D	OFF	301.8	30.6
7/17	28 "	I,D	I,D	OFF	161.1	24.0
7/17	29 "	I,D	I,D	ON	257.0	7.9
7/17	30 "	I,D	I,D	ON	91.0	5.0
7/18	31 (set D)	I(4)	I	ON	183.7	10.9

Notes:

(1) I = Impactor run F = Total filter run
B = Blank impactor run D = Diffusion battery run

(2) Faulty filter holder, no inlet data obtained

(3) Runs 27-31, charge neutralizers connected prior to impactors and also connected on the dust feeder. A cross was installed downstream of the dust feeder to promote mixing.

(4) Alumina used as test aerosol

OPERATING CONDITIONS

The operating conditions of the electrostatic scrubber varied slightly between the first two series of sampling tests. Gas flow rates, water flow rates and other related operating parameters are tabulated for each data set and are given in the Tables 2 and 3 below.

Table 2. DATA SET A, RUNS 1-10

CONDITION	INLET	OUTLET
Temperature	15-21°C	14-20°C
Velocity	8.4m/sec(27.6 ft/sec)	5.1m/sec(16.7 ft/sec)
Am^3/min @16°C	21.0	22.1
ACFM @16°C	740.0	780.0
DNm^3/min @ 0°C	19.6	19.7
DSCFM @21°C	745.0	748.2
Vol. % H_2O vapor	1.1	1.6
Static Pressure	-0.6 cm W.C.	-13.2 cm W.C.
Pressure drop across venturi		40.0 cm W.C.
Pressure drop across separator		2.5 cm W.C.
Ionizer wall wash flow rate		7.6 ℓ/min
Venturi water flow rate		22.7 ℓ/min
*Electrode cooling air		1.1 m^3/min(40 CFM)
L/G ratio		1.4 ℓ/m^3

*Electrode cooling air introduced into system and accounted for as dilution air.

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Table 3. DATA SETS B, C AND D, RUNS 11-31

CONDITION	INLET	OUTLET
Temperature	15-21°C	14-20°C
Velocity	7.5m/sec(24.5 ft/sec)	5.4m/sec(17.8 ft/sec)
Am^3/min @16°C	22.7	23.8
ACFM @16°C	800.0	840.0
DNm^3/min @0°C	21.2	21.2
DSCFM @21°C	805.0	806.0
Vol. % H_2O vapor	1.1	1.6
Static Pressure	-0.6 cm W.C.	-43.2 cm W.C.
Pressure drop across venturi		40.0 cm W.C.
Pressure drop across separator		2.5 cm W.C.
Ionizer wall wash flow rate		7.6 ℓ/min
Venturi water flow rate		34.1 ℓ/min
*Electrode cooling air		1.1 m^3/min (40 CFM)
L/G ratio		1.8 ℓ/m^3

*Electrode cooling air introduced into system and accounted for as dilution air.

CASCADE IMPACTOR PARTICLE DATA

Four separate sets of data were obtained from the A.P.S. electrostatic scrubber as described in the Test Method section. Fully developed flow enabled representative one-point sampling. Identical one-point sample locations were used for all the data points.

Particle concentration and sampled volumes for the total particulate runs taken are given in Table A-1 in Appendix A. Particle concentration, particle size and sampled volumes for cascade impactor runs are tabulated in Appendix A in Tables A-2 through A-23. Size distributions for the impactor runs are given in Figure A-1 through A-11 located in the Appendix.

A summary of the inlet and outlet size distribution tests with the ionizer on and off is given in Table 4.

In this report, the symbol "d_{pa}" refers to aerodynamic diameter, which is equal to the particle diameter (d_p) in microns (μm) times the square root of the particle density (ρ_p) in grams per cubic centimeter (g/cm^3) times the square root of the Cunningham slip correction factor (C'). The symbol "μmA" represents the units of aerodynamic size.

$$d_{pa} = d_p \left(\rho_p C'\right)^{1/2}, \ \mu mA \qquad (1)$$

The symbol "d_{pc}" refers to the aerodynamic cut diameter or the particle diameter in which the impactor stage collection efficiency is 50%. The "d_{pc}" may also refer to the aerodynamic cut diameter of the control device in which, at the given particle diameter, the penetration is equal to 0.50. The symbol "d_{pg}" refers to the mass mean aerodynamic particle diameter for a given size distribution.

Table 4.- Inlet and Outlet Size Distribution Summary

Run Set No.		Ionizer	INLET		OUTLET	
			d_{pg}, μmA	σ_g	d_{pg}, μmA	σ_g
2	A	ON	0.95	2.2	0.90	1.7
3		ON	0.95	2.2	0.90	1.7
4		ON	0.95	2.2	0.90	1.7
5		OFF	1.1	2.3	1.0	1.9
6		OFF	1.1	2.3	1.0	1.9
11	B	ON	0.90	2.0	0.85	1.6
13		ON	0.90	2.0	0.85	1.6
14		OFF	1.0	2.3	0.95	1.8
16		OFF	1.2	2.3	0.95	1.8
18		ON	1.2	2.3	0.90	1.7
20		ON	1.1	1.9	0.90	1.7
21		ON	0.94	1.9	--------	--------
22		ON	0.94	1.9	--------	--------
23		ON	0.94	1.9	--------	--------
24		ON	0.97	2.2	1.1	1.8
25		OFF	--------	--------	0.92	1.8
26		OFF	1.2	2.1	--------	--------
27	C	OFF	1.5	2.0	1.3	1.8
28		OFF	1.4	1.8	1.1	1.9
29		ON	1.8	1.9	1.1	1.5
30		ON	2.1	2.1	1.4	1.5
31	D	ON	1.9	2.3	1.2	2.1

Average sample times for the inlet were twenty to thirty minutes depending on the mass loading, while the outlet sample times averaged approximately one hour.

Isokinetic sampling was undertaken for all the test runs, however, isokinetic conditions are not that crucial for sampling fine particles. For example, the error caused by sampling 4 μmA particles at a velocity 50% higher or lower than the gas stream velocity would only be about 2 or 3% of the concentration.

Single point sampling is also generally sufficient when measuring fine particle size and concentration. The fine particles will be distributed well in the gas stream, except in cases where streams with different particle concentrations have not had sufficient time to mix. To illustrate that one point sampling is sufficient for fine particles, we may note that Stokes stopping distance of a 3 μmA particle with an initial velocity of 15 m/sec (50 ft/sec) is about 0.04 cm (0.016 inches) and for a 1 μmA diameter particle is one ninth of that. Since the stopping distance is the maximum that a particle can be displaced from a gas streamline by going around a right angle bend, it becomes apparent that fine particle distribution in the gas stream will be negligibly affected by flow direction changes.

The sample data obtained were fairly consistent, depending on operation of the scrubber and the particle feed generator. No inlet data were obtained for Run 1 due to a faulty filter holder. Entrainment problems due to a surge during start up of Run 24 caused heavy loading on the upper stages of the cascade impactor. Figure A-7 shows the outlet size distribution for Run 24 curving upward which is a direct result of the entrainment encountered. Therefore, the upper stage data points were not used in determining the size distribution curve.

The scrubber was tested, using alumina as the test aerosol for Run 31. Due to difficulties in particle generation, this was the only run tested on alumina. Figure A-11 shows that alumina has a d_{pg} of approximately 1.9 with a standard deviation of 2.3.

Diffusion battery particle data taken for Runs 22, 24, and 27 through 30 are described in the following "Diffusion Battery Data" section. The diffusion battery size distributions are given in actual size or d_p, μm. The range of the size distributions is approximately 0.02 μm to 0.50 μm.

DIFFUSION BATTERY DATA

Diffusion battery data were taken during two sampling sessions; June 25-27 and July 17, see Table 1. The runs were made simultaneously with cascade impactors and numbered accordingly. Runs 19-21 were preliminary tests used for adjusting flows and counting techniques. The condensation nuclei counters had mechanical difficulties during Runs 23 and 26; therefore, representative data were not obtained for these runs.

Fluctuations in the particulate loading from day to day prevented comparing inlets (outlets) with outlets (inlets) from the previous day for particle penetration analysis and little valuable information was obtained from the first series of tests. During the second series of tests Runs 27 (inlet and outlet) and 28 (inlet and outlet) were taken with the ionizer off. Runs 29 (inlet and outlet) and 30 (inlet and outlet) were taken with the ionizer in operation. Runs 22 (inlet) and 24 (outlet) were not compared for penetration as the data were taken on separate days. The performance was determined by statistical conversion of inlet-outlet size distributions to cumulative number (mass) concentration and calculating the particle penetrations in the same manner as the cascade impactor analysis.

Figures A-12 through A-17 in Appendix A contain the inlet and outlet size distributions for test Runs 22, 24, and 27 through 30. Diffusion battery penetration data are discussed in the particle penetration section.

PARTICLE PENETRATION

Particle penetration versus particle size was plotted for the data obtained from the electrostatic scrubber. A composite of the runs in data set A is represented in Figure 5, which shows the effect of the ionizer on penetration. Penetrations for the individual runs in sets B and C are shown in Figures 6 and 7. Figure 8 shows composite curves for sets A, B, and C for overall comparison.

It can be seen in Figures 5 through 8 that the ionizer improves the scrubber performance in all cases. However, the amount of improvement is least in data set C, where the most precautions were taken to neutralize and mix the test aerosol entering the scrubber.

The penetrations found by using the diffusion battery are presented in Appendix B along with the individual penetrations for the cascade impactor runs of data set C. Particle density variation and loading fluctuation account for discrepancies between impactor and D.B. penetrations.

The penetration curves indicate an increase in efficiency for particles smaller than the 0.1 to 0.2 μmA range. From these results and published literature, it is evident that smaller, more highly diffusive particles experience increased collection efficiency.

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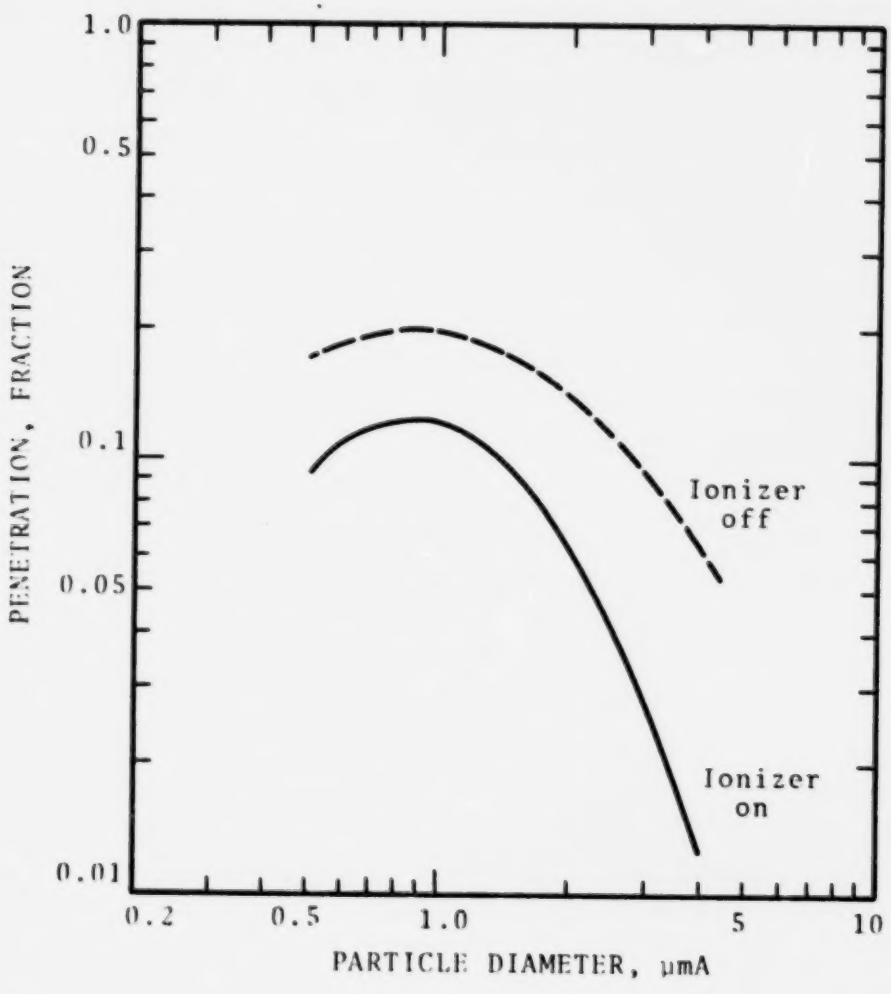

Figure 5. Penetration vs. particle diameter for data set A.

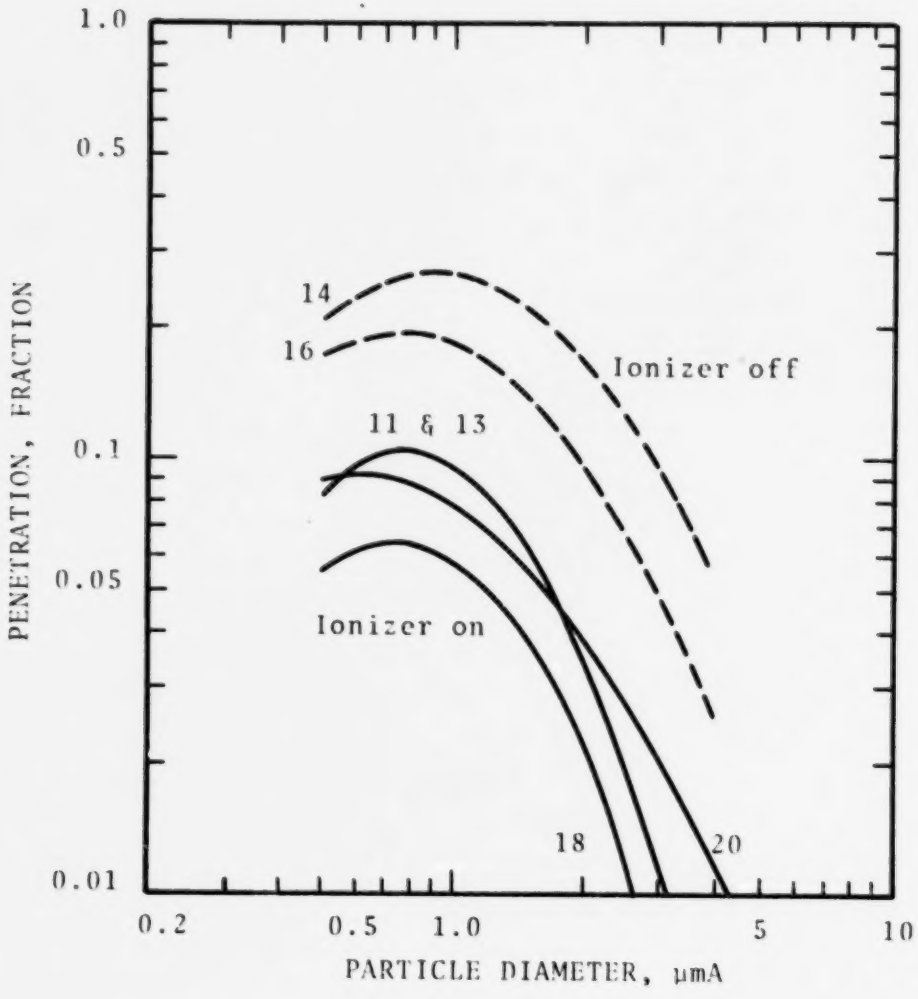

Figure 6. Penetration vs. particle diameter for data set B.

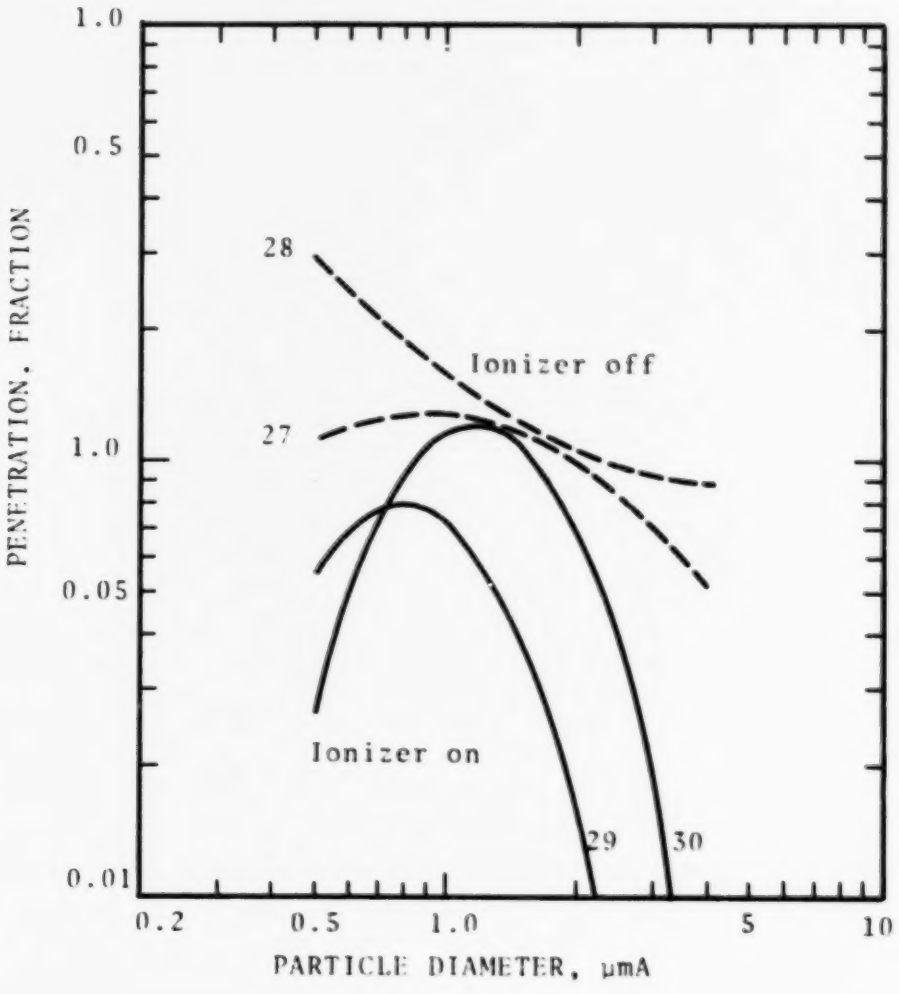

Figure 7. Penetration vs. particle diameter for data set C.

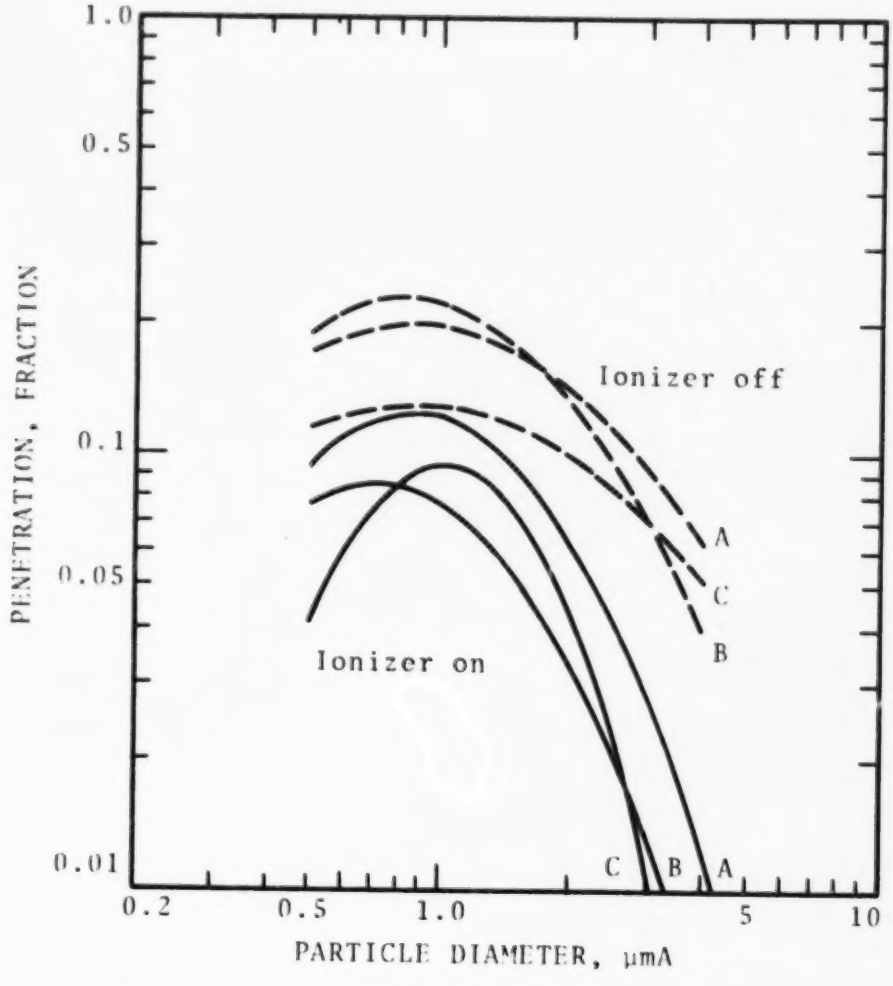

Figure 8. Penetration vs. particle diameter for data sets A, B, & C.

Computation Method

The penetrations described above were computed by means of a machine computation program. This method utilizes inlet and outlet particle size data which are fitted to log-normal distributions. Next the size distribution parameters and the mass concentrations are used to compute penetration as a function of particle size. Diffusion battery data yield penetration related to physical size while cascade impactor data are in terms of aerodynamic size. In order to put the results on the same basis, it is necessary to know the particle density so that one can convert physical size to aerodynamic size (or visa-versa).

Particle size distribution data are conveniently represented on logarithmic probability graph paper. Often the data fit a straight line on log-probability paper, and thus can be mathematically represented by a log-normal size distribution.

Caution must be taken when using a mathematical expression for the penetration. First, the fit of the data to a log-normal distribution must be close. Second, there is uncertainty introduced by extrapolating data beyond the size range measured. The penetration equation should not be used for particle sizes smaller or larger than those measured.

Previous calculations of penetrations have been done by manually and visually determining the ratio of the slopes of the outlet and inlet cumulative mass versus particle size curves at different particle sizes. Penetration versus particle size curves were drawn for the electrostatic scrubber by the visual method and by the machine method described above. The deviations in penetrations between the two methods were generally less than ±0.01 or 1 percent penetration.

Within the limits of the particle sizes measured, the accuracy of the log-normal penetration equation depends only on how well the data fit log-normal distributions. Since the particle size data have many other inaccuracies because of the difficulties of measurement, the log-normal penetration is accurate enough, considering the ease with which it can be used. It is also most advantageous to eliminate the subjective errors possible with the visual method.

An overall penetration summary for Runs 1 through 31 is presented in Table 5. Total inlet and outlet mass loadings were taken by cascade impactors or total filter samples.

The average overall penetration for the electrostatic scrubber with the ionizer on was approximately 8.4%; while the average for the ionizer off was approximately 17% when TiO_2 with a d_{pg} of 1.0 μmA and a σ_g of 2.2 was used as the test aerosol.

Equivalent Cut Diameter

For purposes of comparison it is valuable to have a single parameter which describes the efficiency of a scrubber. The cut diameter (i.e. particle diameter for which the penetration is 50%) has proven to be useful for most scrubbers. There is a problem in applying the method here; however, because the penetration data do not reach 50%. To resolve this dilemma we decided to compute the cut diameter which would be required to give the same overall penetration (i.e., over the entire particle size distribution) if the scrubber had the same penetration vs. pressure drop characteristics as a venturi scrubber. We could alternately have used the equivalent pressure drop that a venturi would need as a criterion for comparison.

The theoretical cut diameter for venturi-type scrubbers can be calculated using Figure 9. For example, if $\sigma_g = 2.2$ and the overall penetration is 0.087 then, using

TABLE 5. OVERALL PENETRATION SUMMARY

Run No.	Ionizer	MASS LOADING mg/DNm³		Overall $\overline{Pt}$ %
		Inlet	Outlet	
1(set A)	ON	-----	1.0	-----
2 "	ON	146.5	12.8	8.7
3 "	ON	156.1	12.0	7.7
4 "	ON	188.5	16.1	8.5
5 "	OFF	524.6	75.2	14.3
6 "	OFF	396.1	62.1	15.7
7 "	OFF	185.1	62.4	33.7
8 "	OFF	927.9	108.2	11.7
9 "	ON	1081.2	37.7	3.5
10 "	OFF	218.7	41.8	19.1
11(set B)	ON	152.7	10.3	6.7
12 "	ON	132.0	13.8	10.5
13 "	ON	153.4	11.4	7.4
14 "	OFF	216.9	40.8	18.8
15 "	OFF	594.2	79.2	13.3
16 "	OFF	516.9	65.1	12.6
17 "	ON	472.4	24.2	5.1
18 "	ON	495.9	18.4	3.7
19 "	ON	69.4	8.4	12.1
20 "	ON	192.2	12.5	6.5
21 "	ON	48.1	8.1	16.8
22 "	ON	53.7	7.6	14.2
23 "	ON	100.1	10.3	10.3
24 "	ON	85.1	12.7	14.9
25 "	OFF	153.9	31.8	20.7
26 "	OFF	102.6	21.3	20.8
27(set C)	OFF	301.8	32.1	10.6
28 "	OFF	161.1	24.0	14.9
29 "	ON	257.0	7.9	3.1
30 "	ON	91.0	5.0	5.5
31(set D)	ON	183.7	10.9	5.9

Figure 9, the ratio of cut to mass mean diameters is approximately 0.31. For d_{pg} = 0.95 μmA and using the above ratio of cut to mass mean diameter the theoretical aerodynamic cut size, "$d_{p\,50}$," is 0.29. The cut diameter computed by this method is that which would be provided by a conventional high energy (venturi type) scrubber which would give overall penetration equivalent to the subject scrubber, and it is referred to as the "equivalent cut diameter" in this report.

Equivalent cut diameters were calculated with the same procedure described above for each impactor run and have been tabulated in Table 6. The average cut diameters for various data sets are given in Table 7.

Tables 6 and 7 show a significant increase in equivalent cut diameters when charge neutralizers were used to eliminate static charges induced by the dust feeder. One possible explanation for the increase in the equivalent cut diameters involve a space charge effect in the impactor. Electrostatic charges of the particles tend to bias the inertial impaction collection mechanism of the cascade impactor. This effect of particle charge is evident in the experimental data in which the average d_{pg} increased from 1.0 μmA to 1.7 μmA when the charge neutralizers were used.

Figure 10 represents a plot of pressure drop (cm W.C.) and theoretical power W/(m³/min) versus aerodynamic cut diameters in which "f" is an empirical constant which is influenced by particle wettability and other factors for venturis. The A.P.S. system with the ionizer on had an average equivalent cut diameter of 0.35 μmA at 40 cm W.C., which can be compared to different scrubbers systems using Figure 10.

A venturi with equivalent overall collection efficiency and cut diameter, assuming f = 0.5 as is commonly observed, would have a pressure drop of approximately 100 cm W.C. and

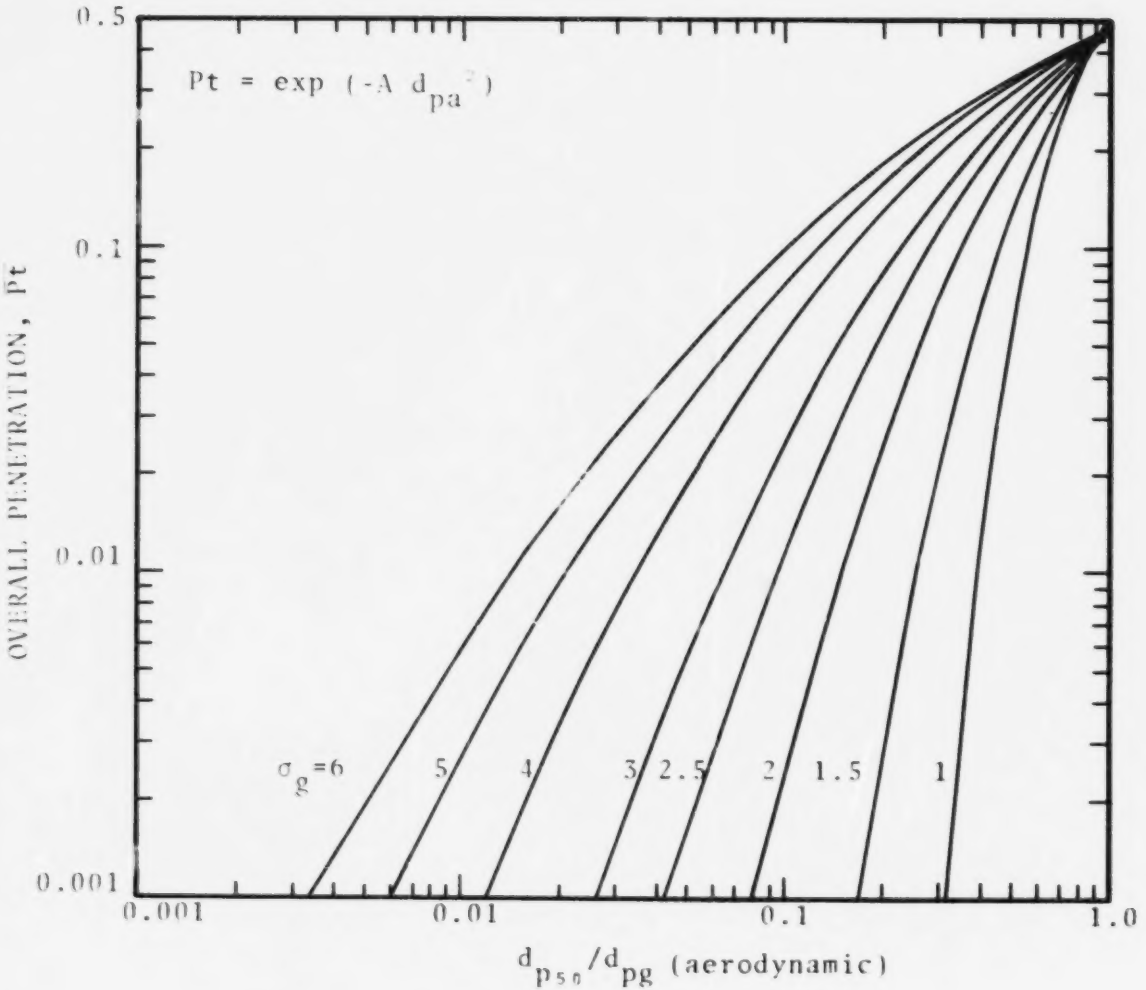

Figure 9. Overall penetration vs. cut to mass mean particle diameter ratio for log-normally distributed particles. (Calvert, et. al., 1972).

Table 6. EQUIVALENT VENTURI CUT DIAMETER SUMMARY

Run No.	Set	Ioni-zer	d_{pg}, µmA	σ_g	$\overline{Pt}$	d_{Pso}/d_{pg}	d_{Pso}, µmA
2	A	On	0.95	2.2	0.087	0.31	0.29
3		On	0.95	2.2	0.077	0.28	0.27
4		On	0.95	2.2	0.085	0.30	0.29
5		Off	1.1	2.3	0.143	0.38	0.42
6		Off	1.1	2.3	0.157	0.41	0.45
11	B	On	0.90	2.0	0.067	0.29	0.26
13		On	0.90	2.0	0.074	0.31	0.32
14		Off	1.0	2.3	0.188	0.45	0.45
16		Off	1.2	2.3	0.126	0.35	0.42
18		On	1.2	2.3	0.037	0.19	0.23
20		On	1.1	1.9	0.065	0.31	0.34
24		On	0.97	2.2	0.149	0.41	0.40
27	C*	Off	1.5	2.0	0.106	0.36	0.54
28		Off	1.4	1.8	0.149	0.47	0.66
29		On	1.8	1.9	0.031	0.23	0.41
30		On	2.1	2.1	0.055	0.25	0.53
31	D*	On	1.9	2.3	0.059	0.24	0.46

*Note: Charge neutralizers used.

Table 7. AVERAGE EQUIVALENT VENTURI CUT DIAMETERS

	Average d_{D50}, μmA	
Data Set	Ionizer On	Ionizer Off
A	0.28	0.44
B	0.31	0.44
C *	0.47	0.60
D *	0.46	--
A&B	0.30	0.44
ALL	0.35	0.49

* Note: Charge neutralizers used.

a theoretical power usage of 170 W/(m^3/min). The theoretical power usage for the A.P.S. system would be approximately 67 W/(m^3/min). Power usage of the ionizer is about 13W/(m^3/min) since it operates at 86 kV and 3.4 milliamperes.

With ionizer off, the overall average penetration of the A.P.S. system was 0.17, corresponding to a cut diameter of 0.45 at a pressure drop across the venturi of 40 cm W.C. This is not in agreement with the general correlation of cut diameter with pressure drop for venturi scrubbers. It is possible that the charging effect of the dust feeder may have some influence on the collection mechanisms of the scrubber when the ionizer is off.

When the dust feeder charge neutralizers were used with the ionizer off the $d_{p_{50}}$ was computed to be 0.60 μmA. This corresponds closely to the correlation of cut diameter with pressure drop for venturi scrubbers, which is what the A.P.S. system is with the ionizer off. This is evidence that results obtained when the dust feeder was operated without a charge neutralizer were influenced by charged dust particles.

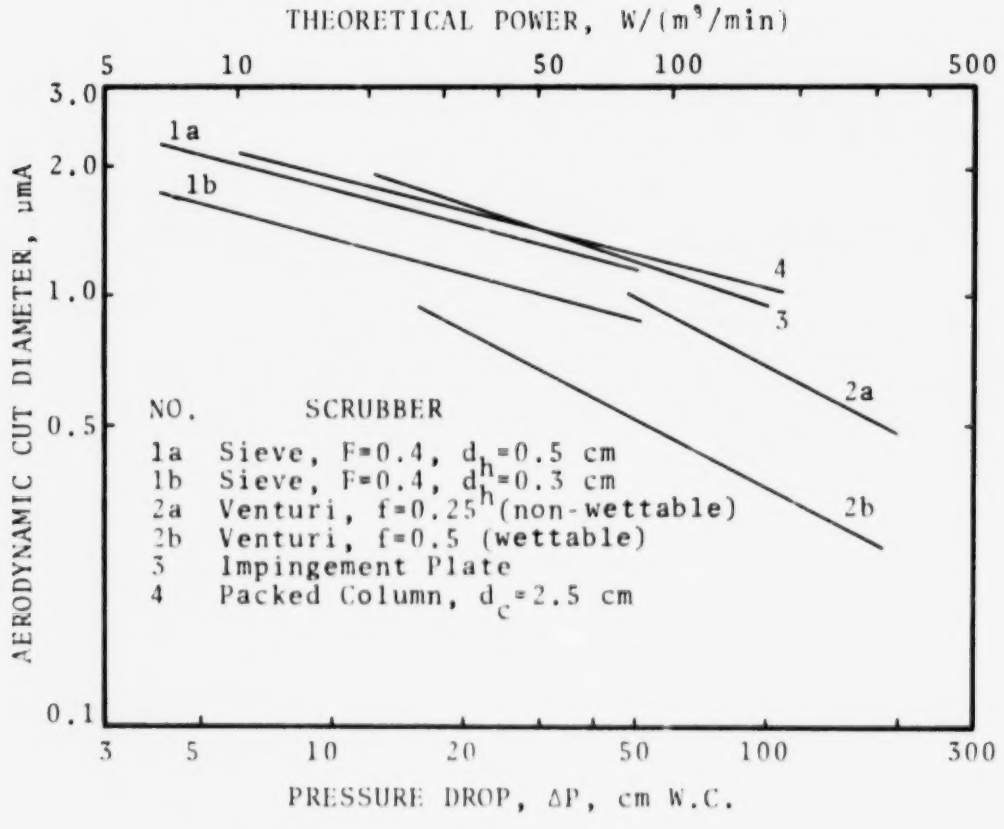

Figure 10 - Representative cut diameters as a function of pressure drop for several scrubber types, (Calvert, 1974).

ECONOMICS

Cost data for the electrostatic scrubber were not provided by the manufacturer. According to Air Pollution Systems, Inc., it would be impractical to include a scrubber operation and capital cost list due to constant changes in material costs.

A.P.S. is prepared to make competitive bids which will depend largely upon customer evaluations of:

1. Equipment performance both mechanically and in meeting guarantees.
2. Power usage and operating costs.
3. Savings in fan, flue, etc. materials as they accure from lower pressure drop.

By using the test data results, it is possible to draw an operating cost comparison between the A.P.S. system and other conventional high energy scrubbers. In the venturi comparison section, several equivalent venturi aerodynamic cut diameters were computed in Table 6 for the A.P.S. system with a venturi pressure drop of 40 cm W.C. Using Table 6 and Figure 10 which represents a plot of pressure drop (cm W.C.) and theoretical power $W/(m^3/min)$ versus aerodynamic cut diameter, an economic comparison can be drawn. One can estimate the operating cost savings which results from operation with the ionizer on by comparing the power required to give the equivalent cut diameter for both the A.P.S. system and for a conventional high energy scrubber.

At a cut diameter of 0.47 μmA, a conventional scrubber would require a pressure drop of about 60 cm W.C. and theoretical power of about 100 $W/(m^3/min)$, while the A.P.S. venturi pressure drop was 40 cm W.C. and theoretical power was 67 $W(m^3/min)$ for fan + 13 $W(m^3/min)$ for ionizer = 80 $W/(m^3/min)$. Assuming a power cost of 3¢/kWH and overall fan and motor efficiency of 50%, the operating costs for

several hypothetical cut diameters are computed to be as shown in Table 8 below.

Table 8. ESTIMATED OPERATING COST COMPARISONS FOR IONIZER ON OPERATION

Data Set	Hypothetical $d_{p_{50}}$, μmA	APS Cost $/10³m³	Conventional Scrubber		Op.Cost Savings $/10³m³
			W/(m³/min)	$/10³m³	
A	0.30	0.074	240	0.240	0.166
B	0.35	0.074	170	0.170	0.096
C	0.47	0.074	100	0.100	0.026

The annual cost savings for a 283 m³/min (10,000 CFM) scrubber operating 8,000 hr/yr would be $22,500/yr for data set A, $13,000/yr for set B, and $ 3,530/yr for set C.

PERFORMANCE MODEL

The prediction of particle penetration for the A.P.S. Electrostatic Scrubber required the development of a mathematical model because none was available from either A.P.S. or the literature. The following section presents the derivation of a predictive model by means of the unit mechanisms approach. While the form of the equation is the consequence of theoretical relationships, an empirical constant, f, is included and its value was assumed to be the same as for non-charged venturi scrubbers.

In a venturi scrubber the most important unit mechanism responsible for particle collection is the collection by drops and the predominant collection phenomenon is inertial impaction. When particles are charged, then in addition to the inertia force, electrostatic forces are present that force the particle towards the drop, i.e. increase the collection efficiency of the drop.

Calvert, et al (1973) calculated the theoretical increase in collection efficiency due to particle deposition caused by flux forces. A plot given by them is shown in Figure 11, a plot of single drop collection efficiency against inertial impaction parameter, with flux deposition number, N_{FD}, as parameter. Inertial impaction parameter and flux deposition number are defined by the following equations:

$$K_p = \frac{C' \rho_p u_o d_p^2}{9 \mu_G d_d} \tag{2}$$

$$N_{FD} = \frac{u_F}{u_o} = \frac{\text{Particle electrostatic deposition velocity}}{\text{Fluid velocity past sphere}} \tag{3}$$

where K_p = inertial impaction parameter
C' = Cunningham slip factor
ρ_p = particle density, g/cm^3
d_p = particle diameter, cm
μ_G = gas viscosity, poise

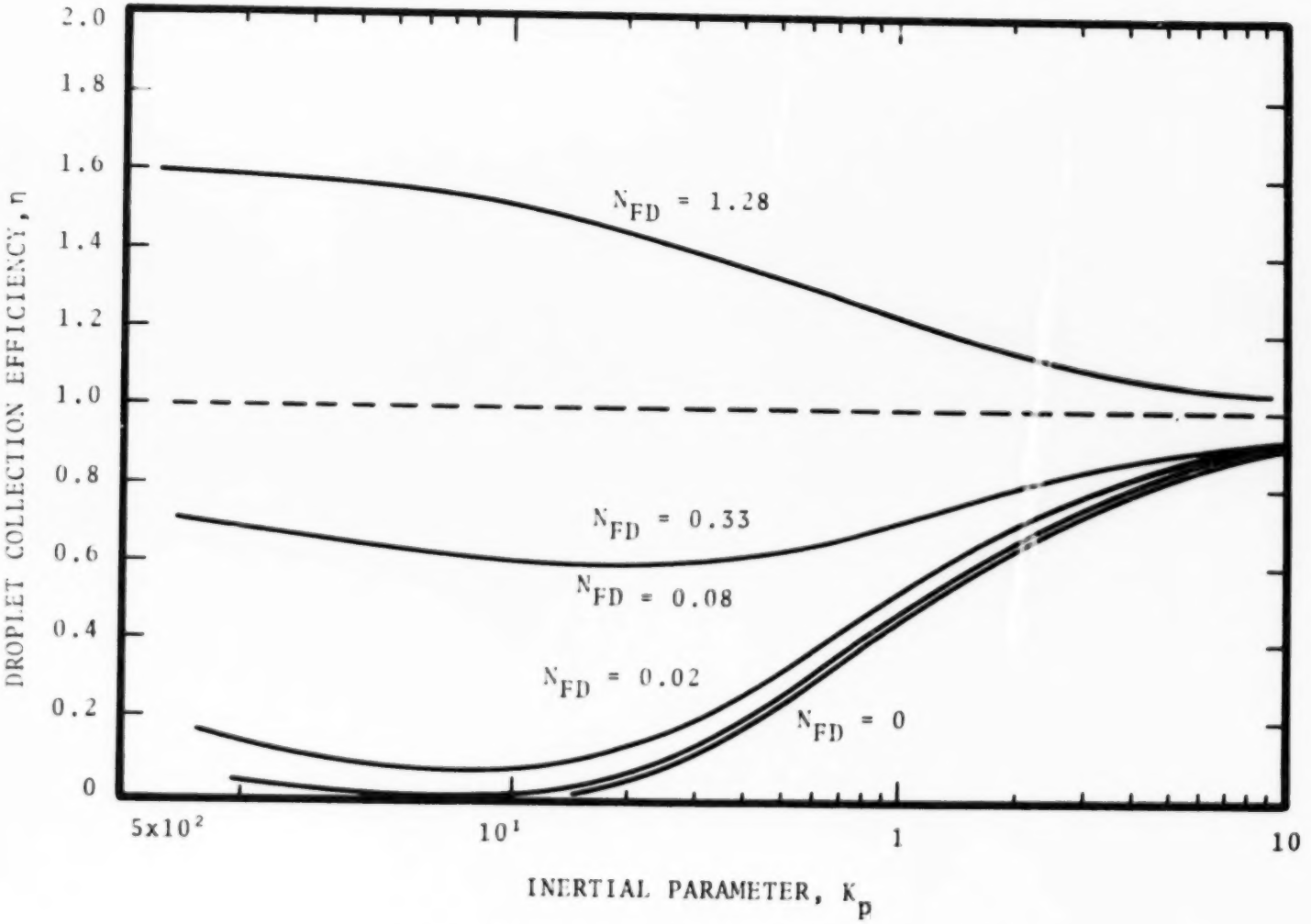

Figure 11 - Efficiency of single drop versus inertia parameter at N_{Red} = 9.6 with N_{FD} as parameter

d_d = drop diameter, cm

u_o = relative velocity between drop and particle, cm/sec

u_F = particle drift velocity or particle transport by electrostatic force, cm/sec

Assume Stokes law holds, then the particle drift velocity is given by:

$$u_F = \frac{C' Q_p E}{3\pi \mu_G d_p} \tag{4}$$

Where: E = field strength, KV/cm

Q_p = electrical charge carried by the particle, coulomb.

It is assumed that aerosol particles are charged to saturation after the particles pass through the corona discharge section. If diffusional charge is neglected (this will give conservative results), then according to Oglesby and Nichols (1970), the saturation charge can be calculated from the following equation:

$$Q_p = 3 \frac{\varepsilon}{\varepsilon+2} \pi \varepsilon_o d_p^2 E_o \tag{5}$$

where ε = dielectric constant of the particle

$\varepsilon_o = 8.86 \times 10^{-14}$ coulomb -cm/cm^2-volt

E_o = charging electric field strength, KV/cm

The atomized drop diameter in a venturi is assumed to be the Sauter mean diameter, which is predicted by means of the Nukiyama and Tanasawa correlation

$$d_d = \frac{50}{u_G} + 91.8 \left(\frac{Q_L}{Q_G} \right)^{1.5} \tag{6}$$

where Q_L = volumetric flow rate of liquid, m^3/min

Q_G = volumetric flow rate of gas, m^3/min

u_G = gas velocity, cm/sec

Once 'N_{FD}' and 'K_p' are calculated, single drop collection efficiency can be read from Figure 11. Single drop collection efficiency 'η' is then related to penetration based on an equation given by Calvert (1968) for a venturi,

$$Pt_i = \frac{2Q_L \rho_L d_d u_{Gt}}{55\ Q_G u_G} \int_{f_a}^{0} \eta_i \, df \qquad (7)$$

where Pt_i = particle penetration for particle size "i"

u_{Gt} = venturi throat gas velocity, cm/sec

f = an empirical constant

f_a = initial value of $f \approx 0.5$

ρ_L = liquid density, g/cm^3

This model was applied to predict the collection efficiency of A.P.S. scrubber both with the ionizer on and with the ionizer off. Since the calculation of particle drift velocity (Equation 4) involves the determination of field strength distribution, which is unknown, a constant value equal to the field strength at the gap was used. This assumption will lead to an optimistic drift velocity.

Figure 12 shows the predicted A.P.S. scrubber performance along with experimental curves. As can be seen, the model agrees fairly well with experimental values for large particles but deviates for small particles. This deviation may be caused by omission of diffusion charge which has a great effect on small particles.

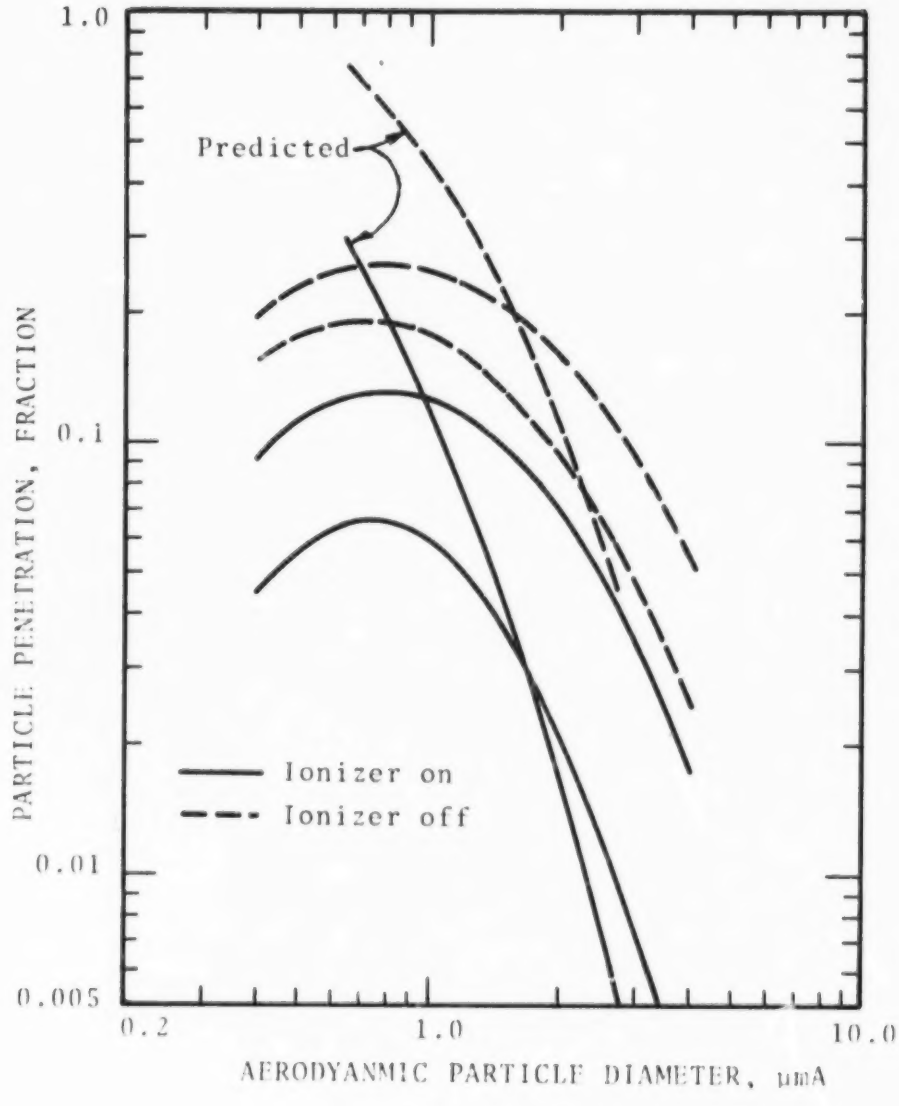

Figure 12. Experimental and predicted particle penetration versus particle diameter.

MANUFACTURER'S DESCRIPTION OF DEVICE

Air Pollution Systems has developed a high intensity ionizer as an electrostatic particle charging device for the purpose of improving the fine particulate collection of conventional scrubbers. A high electrostatic field is generated perpendicular to the gas flow in a radial direction. This special geometry has made possible a stable electrostatic field at a level 3 to 5 times higher than the fields previously possible in conventional precipitators. The higher field strengths have resulted in correspondingly higher particle saturation charge with approximately 7 to 10 times higher gas treatment velocity. This means that high level charging can be accomplished in a much smaller space and packaged into a small add-on device if so desired. The add-on device can also convert existing scrubbers into electrostatically enchanced scrubbers.

The scrubbing collection mechanisms are enhanced by the addition of electrostatic forces to those of inertia, diffusion and other types of flux forces. The electrostatic forces are substantial because of the higher particle charge and are directly additive to all the other forces. The result is a large increase in collection with a small increase in electrical power consumption.

While the ionizer has been developed using a venturi scrubber, the ionizer could be placed in front of most scrubbing devices with a similar increase in efficiency.

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APPENDIX A

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TOTAL LOADING TESTS

Table A-1. TOTAL FILTER PARTICLE LOADING TESTS

RUN NO.	IONIZER	INLET		OUTLET	
		M_{cum} (mg/DNm^3)	DNm^3	M_{cum} (mg/DNm^3)	DNm^3
1 (Set A)	ON	----	--	1.0	1.21
7 "	OFF	185.1	0.19	62.4	0.55
8 "	OFF	927.9	0.08	108.2	0.40
9 "	ON	1081.2	0.04	37.7	0.53
10 "	OFF	218.7	0.20	41.8	0.60
12 (Set B)	ON	132.0	0.16	13.8	0.66
15 "	OFF	594.2	0.09	79.2	0.35
17 "	ON	472.4	0.13	24.2	0.66
19 "	ON	69.4	0.50	8.4	0.90

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Table A-2. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 2

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle	147		12.8	
1	146	26.2	12.8	20.4
2	144	11.5	12.6	8.9
3	142	5.4	12.5	3.4
4	141	2.2	12.2	1.7
5	123	1.3	11.4	1.0
6	94.3	0.7	8.17	0.55
7	51.6	0.43	2.12	0.32
Filter	22.2		0.88	
Sample Volume (DNm³)	0.50		2.38	

Table A-3. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 3

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle	156		12.0	
1	156	26.2	12.0	20.3
2	154	11.5	11.6	8.9
3	153	4.4	11.6	3.4
4	150	2.2	11.6	1.7
5	137	1.3	10.9	1.0
6	106	0.71	7.12	0.55
7	53.0	0.43	1.78	0.32
Filter	18.2		0.31	
Sample Volume (DNm³)	0.37		2.07	

Table A-4. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 4

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle	188		16.1	
1	188	26.4	15.9	20.2
2	187	11.6	15.6	8.8
3	187	5.5	15.5	3.4
4	185	2.3	15.3	1.7
5	164	1.3	14.1	0.99
6	124	0.71	10.0	0.55
7	66.9	0.43	2.68	0.32
Filter	27.6		0.96	
Sample Volume (DNm³)	0.37		2.08	

Table A-5. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #5

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle	525		75.2	
1	519	26.2	75.2	21.0
2	509	11.5	75.1	9.2
3	504	4.4	75.1	3.6
4	481	2.2	73.0	1.8
5	410	1.3	60.8	1.0
6	290	0.71	35.4	0.57
7	145	0.43	11.0	0.33
Filter	60.5		2.25	
Sample Volume (DNm³)	0.32		1.55	

Table A-6. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #6

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle	396		62.1	
1	393	26.1	62.0	20.7
2	388	11.4	61.8	9.1
3	384	5.4	61.6	3.5
4	374	2.2	60.7	1.8
5	316	1.3	53.7	1.0
6	227	0.71	34.8	0.56
7	124	0.43	10.2	0.32
Filter	52.3		2.89	
Sample Volume (DNm³)	0.25		0.98	

Table A-7. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #11

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	153	26.3	10.3	19.7
2	152	11.5	10.2	8.6
3	151	5.4	10.2	3.3
4	150	2.2	10.1	1.7
5	135	1.3	9.7	0.96
6	104	0.71	6.7	0.53
7	57.5	0.43	1.1	0.31
Filter	22.8		0.45	
Sample Volume (DNm³)	0.37		1.64	

Table A-8. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #13

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	153	25.9	11.4	23.4
2	153	11.3	11.1	10.3
3	153	4.4	11.0	4.0
4	151	2.2	11.0	2.0
5	138	1.3	10.5	1.1
6	10	0.70	8.30	0.63
7	50.7	0.42	3.20	0.37
Filter	18.4		0.41	
Sample Volume (DNm³)	0.38		1.54	

Table A-9. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #14

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	217	25.6	40.8	24.0
2	215	11.2	40.6	10.5
3	212	5.3	40.3	4.1
4	209	2.2	39.8	2.0
5	180	1.3	37.0	1.2
6	133	0.69	28.1	0.65
7	71.1	0.42	10.1	0.37
Filter	32.2		2.5	
Sample Volume (DNm³)	0.34		1.11	

Table A-10 INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #16

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	517	25.4	65.1	24.0
2	509	11.1	65.0	10.5
3	507	4.5	64.9	4.1
4	493	2.2	64.5	2.0
5	375	1.2	58.4	1.2
6	269	0.69	40.4	0.65
7	118	0.41	15.0	0.37
Filter	39.9		2.7	
Sample Volume (DNm³)	0.14		0.89	

Table A-11 INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #18

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	496	25.3	18.4	24.0
2	481	11.1	17.7	10.5
3	475	4.5	17.6	4.1
4	463	2.2	17.4	2.1
5	374	1.2	16.8	1.2
6	249	0.68	13.6	0.65
7	115	0.41	4.90	0.37
Filter	42.1		0.75	
Sample Volume (DNm³)	0.12		1.11	

Table A-12 INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #20

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	192	25.5	12.5	25.8
2	188	11.2	12.5	10.4
3	188	4.5	12.0	4.0
4	186	2.2	12.0	2.0
5	167	1.2	11.6	1.2
6	119	0.69	9.1	0.64
7	45.9	0.42	2.9	0.37
Filter	10.6		0.46	
Sample Volume (DNm³)	0.13		0.91	

Table A-13 INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #21

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	48.1	25.5		
2	46.9	11.2		
3	46.9	5.3		
4	45.9	2.2		
5	41.2	1.2		
6	34.2	0.69		
7	14.9	0.42		
Filter	4.1		8.1	
Sample Volume (DNm³)	0.31		0.59	

Table A-14. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #22

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	53.7	25.9		
2	52.9	11.3		
3	52.4	4.4		
4	52.1	2.2		
5	49.0	1.3		
6	39.7	0.70		
7	17.4	0.42		
Filter	5.4		7.6	
Sample Volume (DNm³)	0.39		0.76	

Table A-15.INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #23

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	100	25.9		
2	95.8	11.4		
3	90.2	5.4		
4	88.4	2.2		
5	78.6	1.3		
6	62.3	0.70		
7	33.3	0.42		
Filter	11.4		10.3	
Sample Volume (DNm³)	0.45		0.75	

Table A-16. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #24

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	85.1	25.6	12.7	23.9
2	83.1	11.2	12.4	10.5
3	81.3	5.3	8.6	4.1
4	79.3	2.2	8.3	2.0
5	70.6	1.2	7.8	1.2
6	55.1	0.69	6.4	0.65
7	29.7	0.42	2.5	0.37
Filter	11.4		0.39	
Sample Volume (DNm³)	0.39		1.34	

Table A-17. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #25

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1			31.8	23.6
2			31.4	10.3
3			30.0	4.0
4			29.0	2.0
5			27.4	1.2
6			20.5	0.64
7			7.9	0.38
Filter	154		2.2	
Sample Volume (DNm³)	0.25		0.67	

Table A-18. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 26

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	103.0	25.6		
2	95.3	11.2		
3	92.3	4.3		
4	87.4	2.2		
5	77.1	1.2		
6	60.0	0.69		
7	27.0	0.40		
Filter	6.8		21.8	
Sample Volume (DNm³)	0.26		0.90	

Table A-19. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 27

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	302	25.7	32.1	24.6
2	300	11.3	32.0	10.8
3	295	4.4	31.9	5.1
4	269	2.2	31.1	2.1
5	205	1.3	25.4	1.2
6	118	0.69	14.7	0.67
7	32.0	0.40	5.2	0.40
Filter	6.9		0.78	
Sample Volume (DNm³)	0.12		0.94	

Table A-20. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 28

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	161	25.4	24.0	26.2
2	160	11.2	24.0	11.0
3	159	4.3	23.5	4.3
4	155	2.2	22.9	2.2
5	126	1.2	20.2	1.2
6	67.0	0.69	13.4	0.68
7	16.1	0.40	4.7	0.41
Filter	1.70		1.4	
Sample Volume (DNm³)	0.12		0.81	

Table A-21. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #29

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Nozzle				
1	257	25.7	7.9	25.0
2	249	11.2	7.9	10.9
3	249	4.4	7.9	5.2
4	230	2.2	7.9	2.1
5	167	1.3	7.2	1.2
6	84.8	0.69	4.7	0.68
7	16.4	0.40	0.7	0.41
Filter	0.0		0.0	
Sample Volume (DNm³)	0.12		1.02	

Table A-22. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #30

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)
Nozzle				
1	91.0	25.8	5.0	26.3
2	90.1	11.3	5.0	11.5
3	89.2	4.4	5.0	4.5
4	76.1	2.2	4.7	2.2
5	49.9	1.3	4.3	1.3
6	19.2	0.70	2.4	0.71
7	5.2	0.40	0.23	0.43
Filter	0.9		0.0	
Sample Volume (DNm^3)	0.11		0.91	

Table A-23. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN # 31

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm^3)	d_{pc} (µmA)	M_{cum} (mg/DNm^3)	d_{pc} (µmA)
Nozzle				
1	184	25.9	10.9	25.2
2	175	11.4	10.8	11.0
3	171	4.4	10.8	5.2
4	151	2.2	10.7	2.2
5	110	1.3	8.4	1.2
6	58.1	0.70	5.2	0.68
7	18.9	0.40	2.3	0.41
Filter	2.6		0.70	
Sample Volume (DNm^3)	0.26		1.80	

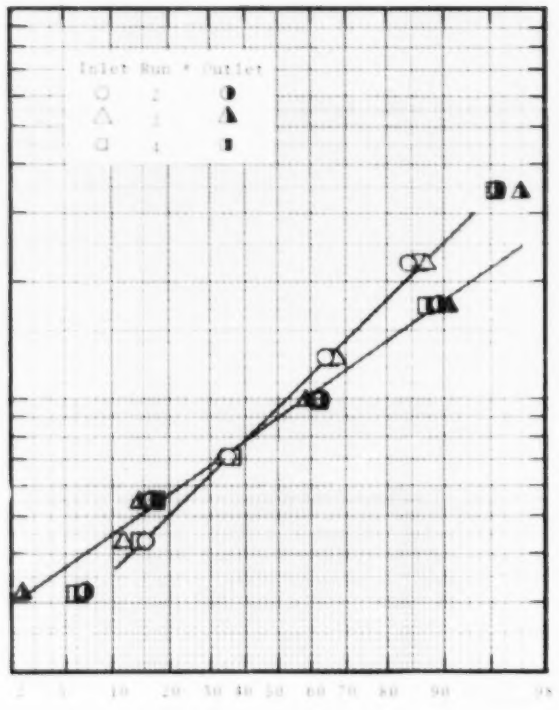

Figure A-1. Inlet and Outlet size distribution for Runs 2, 3 & 4 (Set A, Ionizer on).

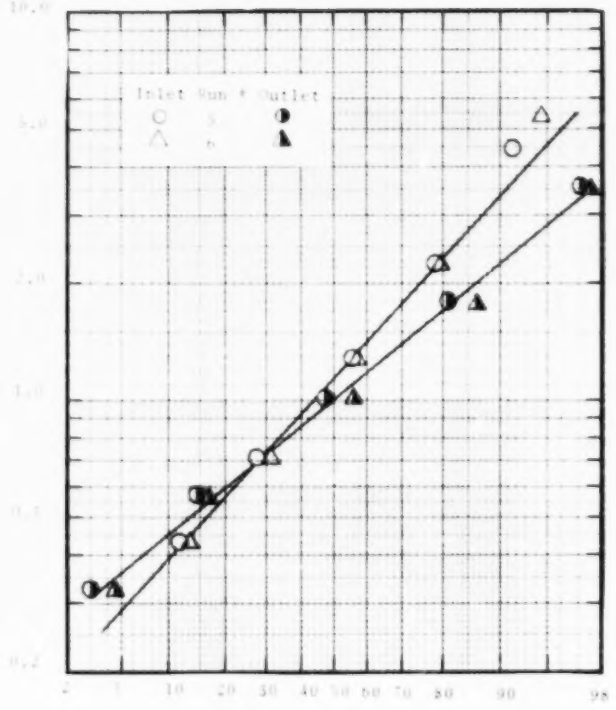

Figure A-2. Inlet and Outlet size distribution for Runs 5 & 6 (Set A, Ionizer off).

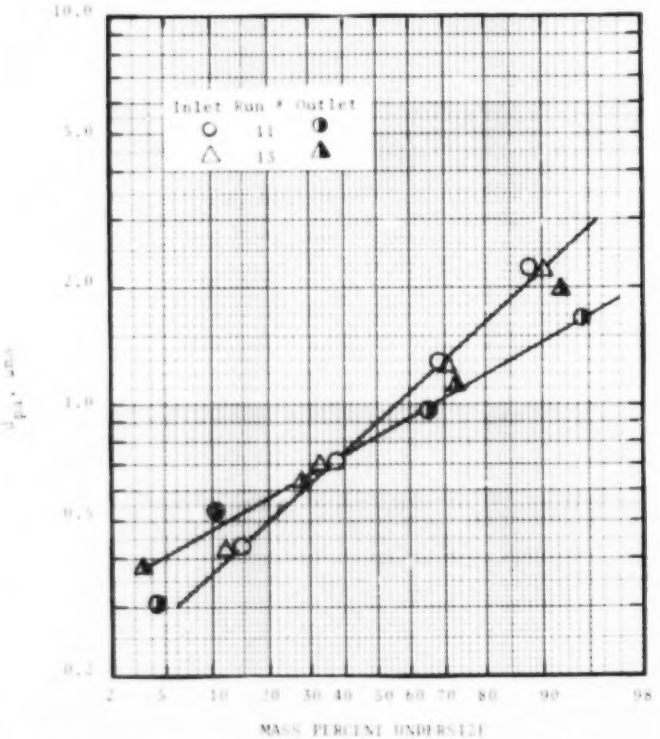

Figure A-3. Inlet and Outlet size distribution for Runs 11 & 13 (Set B, ionizer on).

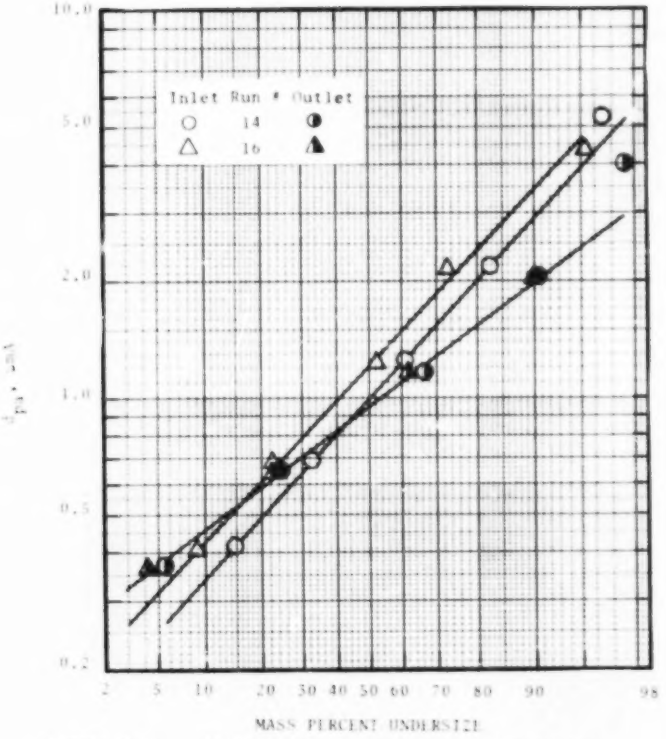

Figure A-4. Inlet and Outlet size distribution for Runs 14 & 16 (Set B, ionizer off).

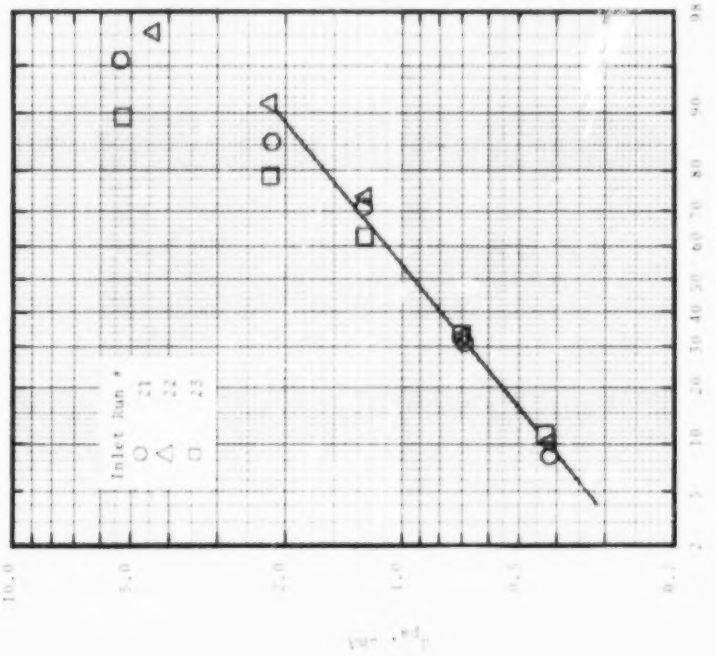

Figure A-4. Inlet size distribution for Runs 21,22 & 23 (Set B, ionizer on).

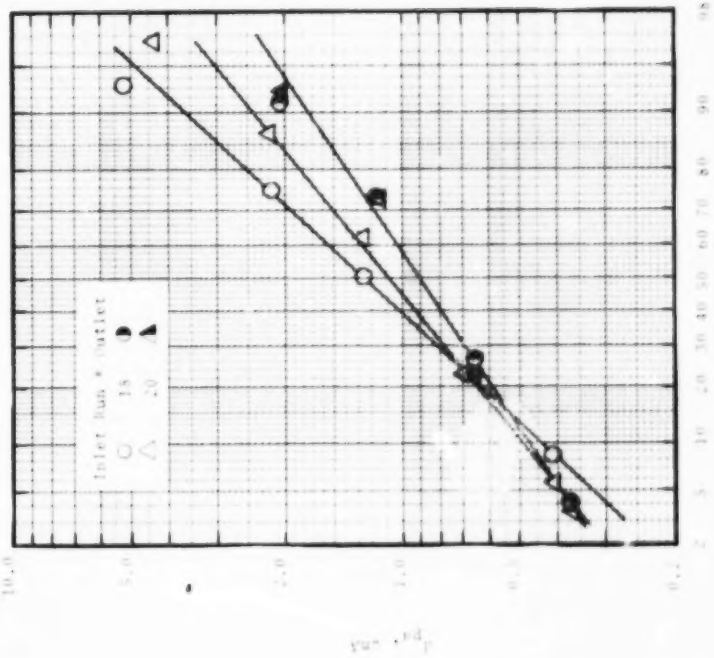

Figure A-5. Inlet and outlet size distribution for Runs 18 & 20 (Set B, ionizer on).

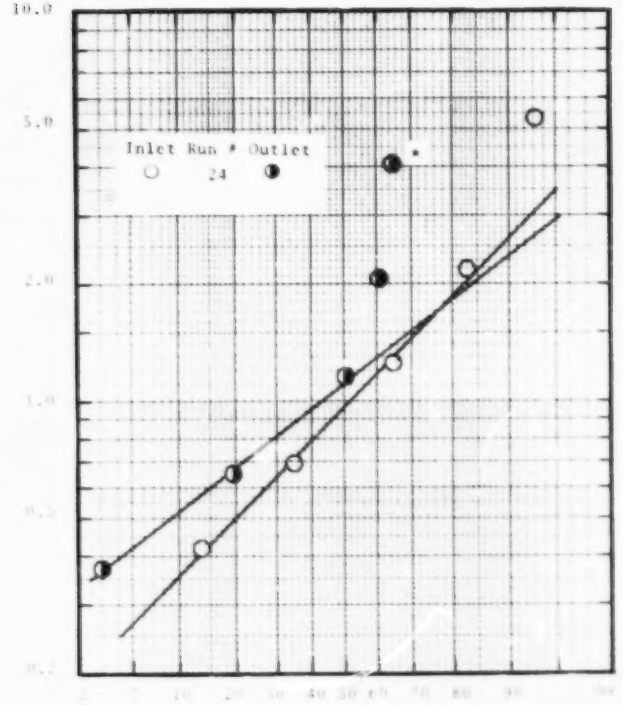

Figure A-7. Inlet and outlet size distribution for Run 24 (Set B, Ionizer on).
*Upper outlet size distribution affected by entrainment

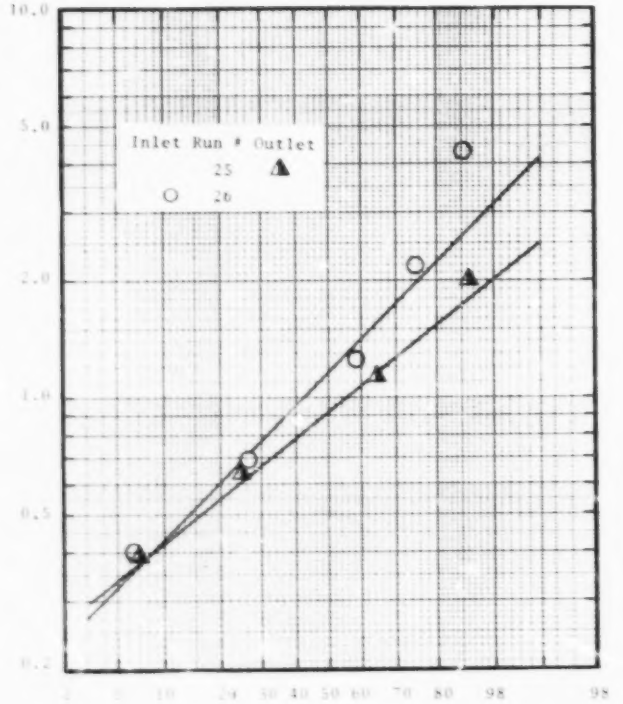

Figure A-8. Inlet and outlet size distribution for Runs 26 & 25 respectively (Set B, Ionizer off).

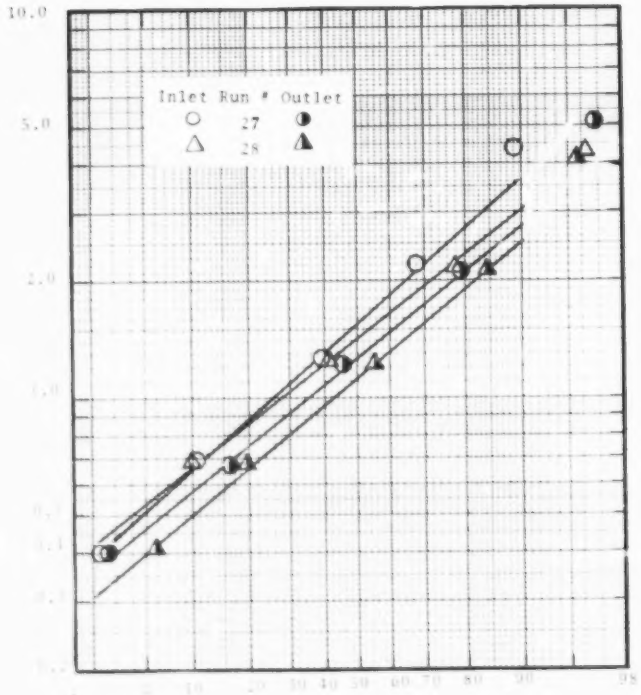

Figure A-9. Inlet and Outlet size distributions for Runs 27 & 28 (Set C, Ionizer off).

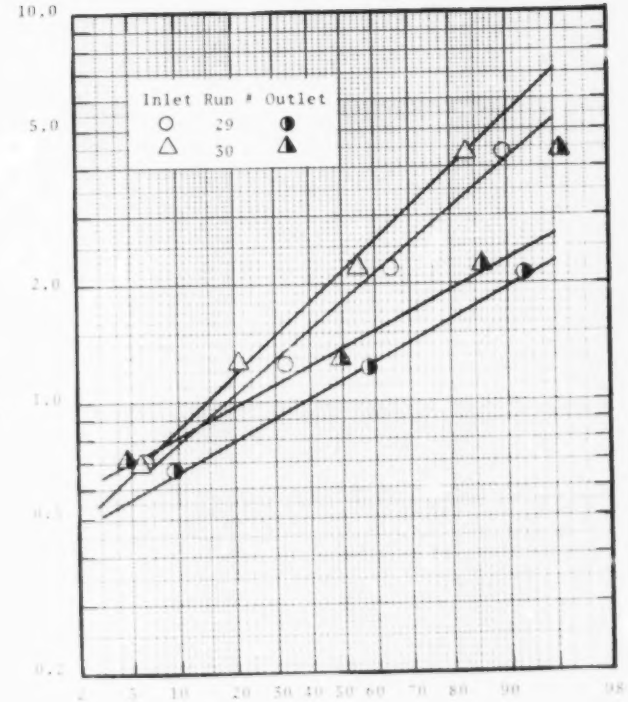

Figure A-10. Inlet and Outlet size distribution for Runs 29 & 30 (Set C, Ionizer on).

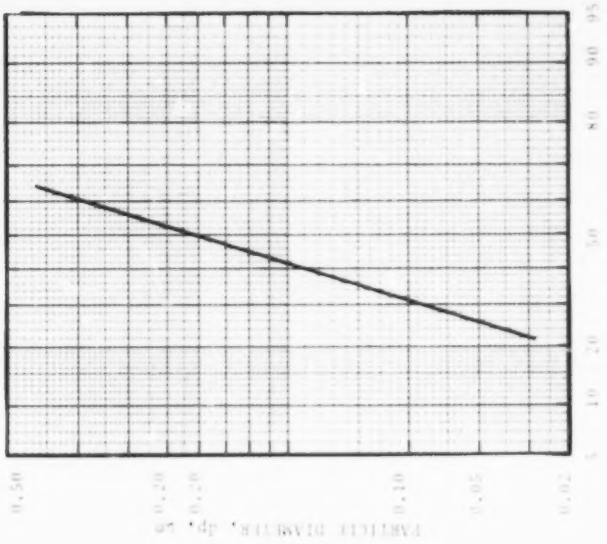

Figure A-12. Precision Battery inlet size distribution for Run 22 (Set B, ionizer on).

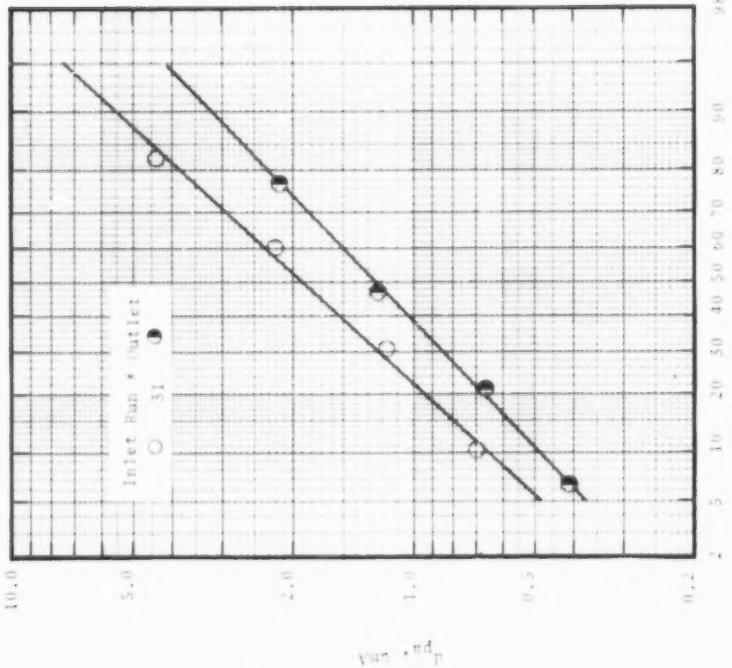

Figure A-11. Inlet and Outlet size distributions for Run 31 (Set D, ionizer on).

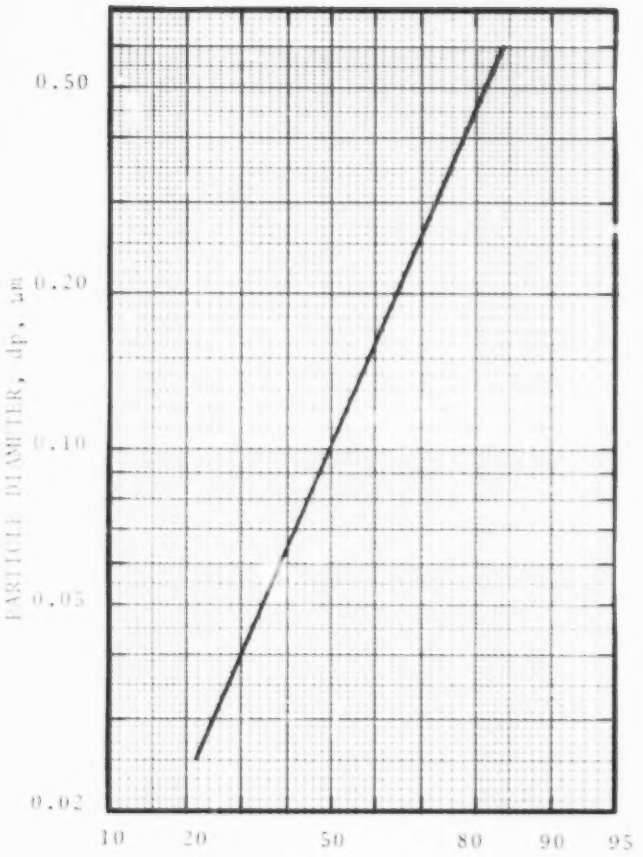

Figure A-13. Diffusion Battery outlet size distribution for Run 24 (Set B, ionizer on).

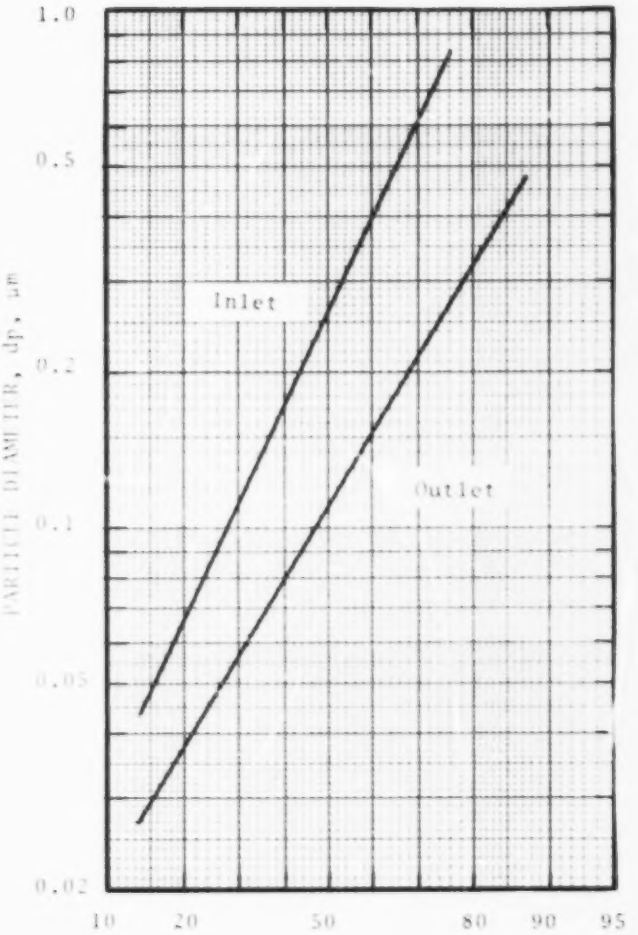

Figure A-14. Diffusion Battery inlet and outlet size distribution for Run 27 (Set C, ionizer off).

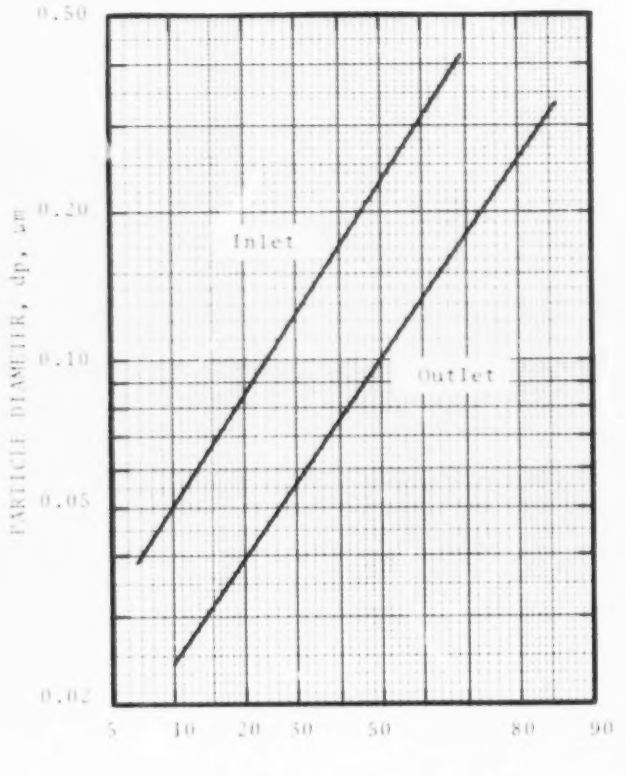

Figure A-15. Diffusion Battery inlet and outlet size distribution for Run 28 (Set C, ionizer off).

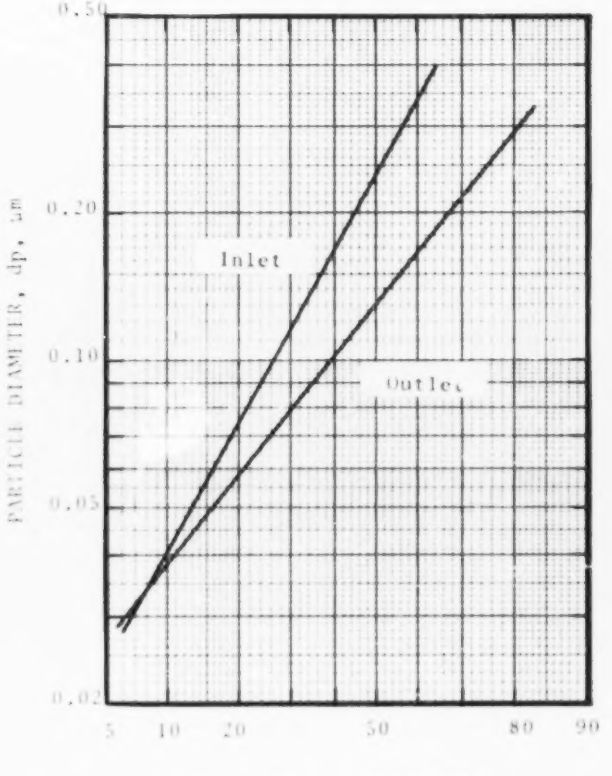

Figure A-16. Diffusion Battery Inlet and Outlet size distribution for Run 29 (Set C, ionizer on).

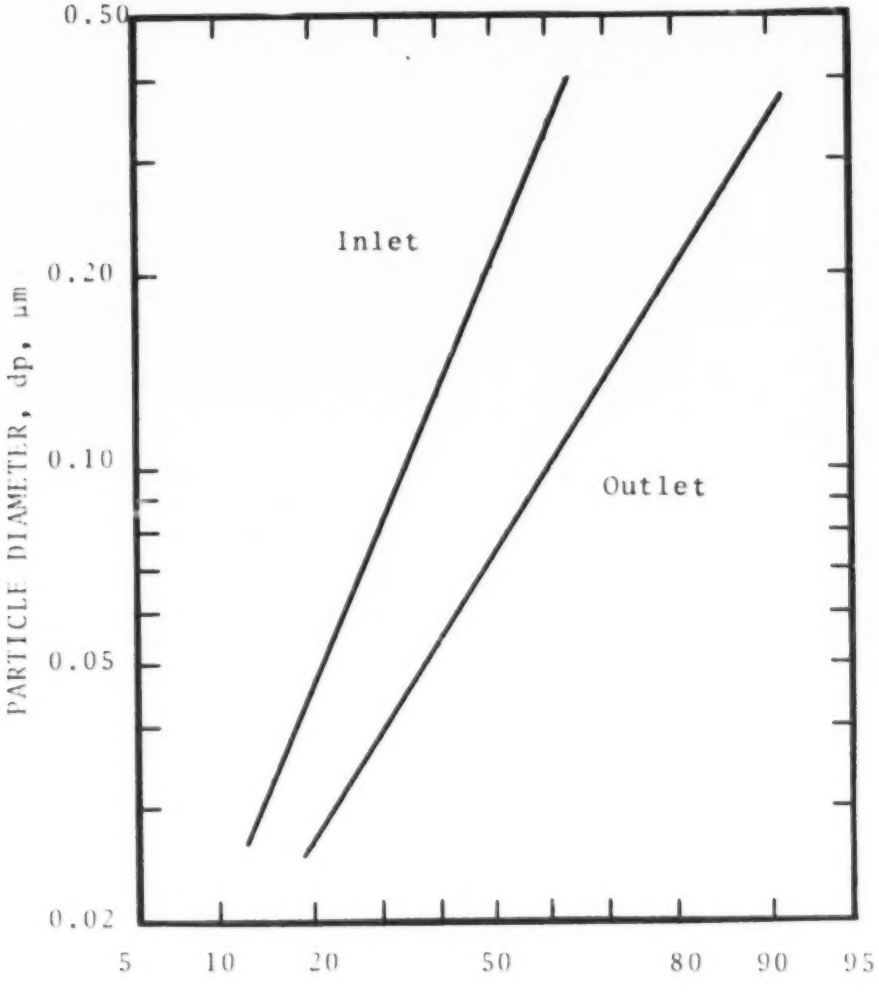

Figure A-17. Diffusion Battery inlet and outlet size distribution for Run 30 (Set C, ionizer on).

APPENDIX B

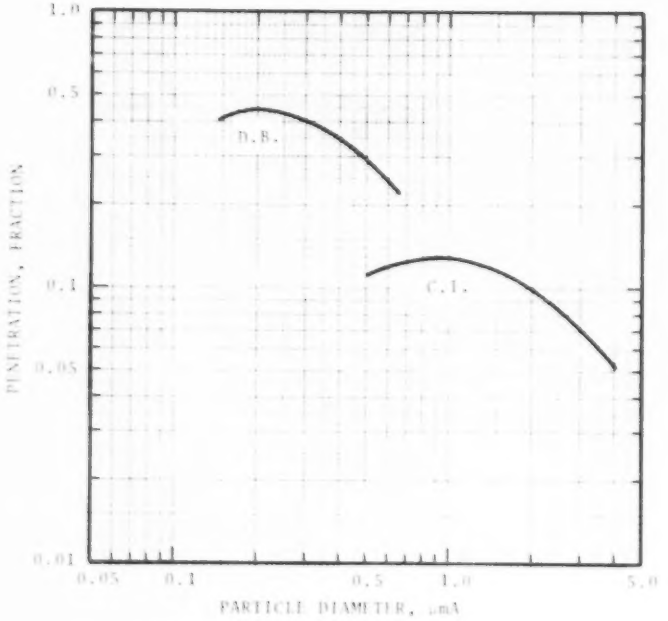

Figure 8-1. Penetration vs. particle diameter using both diffusion battery and cascade impactor, Run 27. (Set C, ionizer off)

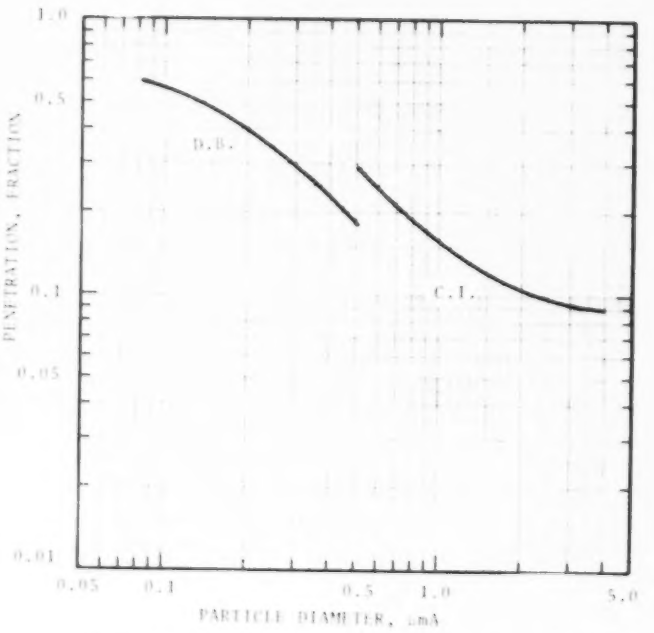

Figure 8-2. Penetration vs. particle diameter using both diffusion battery and cascade impactor, Run 28. (Set C, ionizer off)

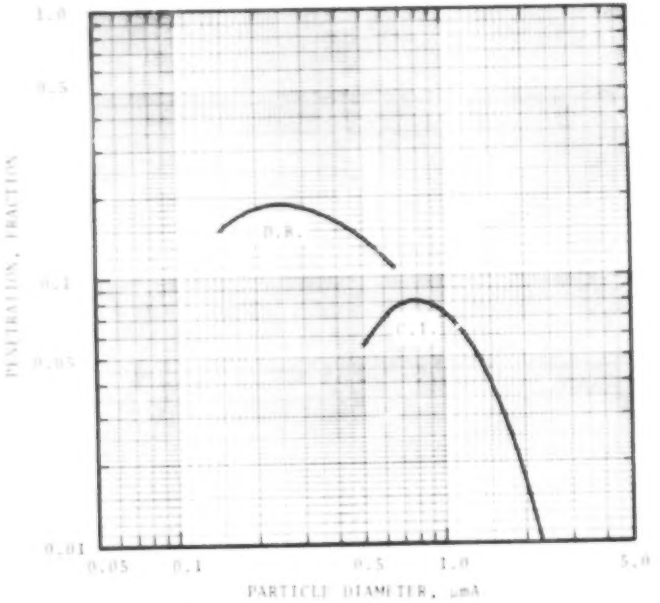

Figure B-3. Penetration vs. particle diameter using both diffusion battery and cascade impactor, Run 29. (Set C, ionizer on)

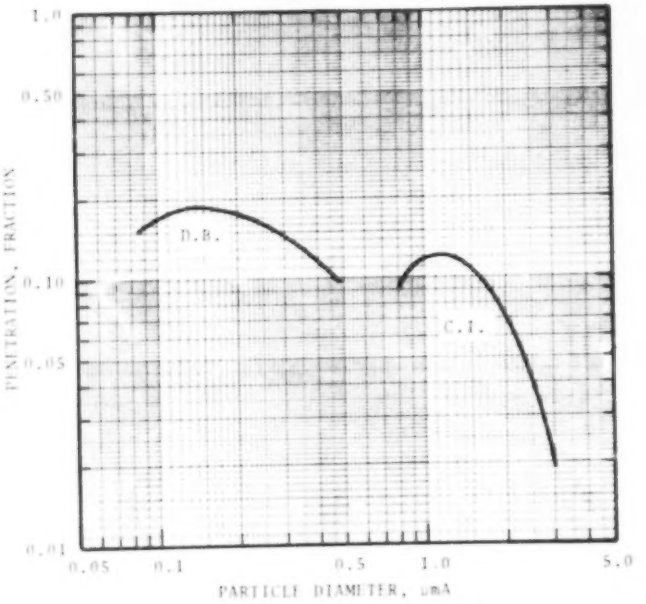

Figure B-4. Penetration vs. particle diameter using both diffusion battery and cascade impactor, Run 30. (Set C, ionizer on)